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| 16. Abstract This study presents a comprehensive evaluation of various adaptive ramp metering strategies in order to identify the optimum algorithm that can help improve traffic conditions on I-12, Baton Rouge, Louisiana. The evaluated ramp metering strategies included the ALINEA local ramp metering control and mixed strategies case which included HERO coordinated and the local ALINEA control. The coordination was performed between three sets of two on-ramps, one on the eastbound and two on the westbound, while the other on-ramps were operating as ALINEA. The different strategies were compared to the current ramp metering strategy that was fixed-time. Geometric and traffic data were collected to build and calibrate a simulation model to be used to test the different ramp metering strategies. Comparative evaluation was then performed on the simulation results of the three strategies using three performance measures: travel time, speed, and vehicle hours travelled (VHT). The three measures were aggregated for the entire corridor and averaged for different sections on the corridor while each section was representing a ramp metering location. The evaluation was conducted separately for the eastbound and westbound directions. For the eastbound direction, the average travel time reduction was 2 seconds for ALINEA and 6 seconds for the mixed strategy case. For the travel speed, the average increase in speed was 0.2 mph for the ALINEA control and 0.4 mph for the mixed strategy. For the VHT, the average reduction was 2.5 veh.hrs for the ALINEA control and 6.5 veh.hrs for the mixed strategy case. On the other hand, for the westbound direction, the results showed more significant improvements. The average travel time reduction increased to 20 seconds for ALINEA control and 40 seconds for the mixed strategy case. For the travel speed, the average increase in speed was one mph for the ALINEA control and 2 mph for the mixed strategy. For the VHT, the average reduction was 195 veh.hrs for the ALINEA control and went up to 197 veh.hrs for the mixed strategy case. The statistical analysis on these results showed that while the improvements were not significant for the eastbound, they were significant for the westbound direction. Yet, most of the results were not considered practically significant. Therefore, more detailed section-by-section analysis was performed using the calculated performance measures for each section on the corridor. The section-by-section analysis showed that none of the eastbound sections experienced any significant improvements. Whereas, on the westbound direction, three sections experienced significant improvements in the different performance measures: Range-O'neal, O'neal-Millerville, and Millerville Sherwood. The travel time reductions on these sections were as high as 45 seconds and 30 seconds for ALINEA and the mixed strategies, respectively. The increase in speed was 9 mph and 13 mph for ALINEA and the mixed strategies, respectively. For the VHT, both strategies achieved reductions that reached 100 veh.hrs for the three sections. When the ALINEA and mixed strategies were compared to one another, the mixed strategy showed more significant improvements. In summary, the eastbound did not experience any significant improvements in the traffic conditions. This is expected since this direction is operating at free flow conditions with the fixed-time strategy. On the other hand, for the westbound directions, the mixed strategy improved the traffic conditions significantly compared to the other control strategies. Yet, the achieved improvements were not as significant as expected. This was caused by the spillbacks at the off-ramps resulting from the vehicles waiting at the red traffic signals on the surface streets. Therefore, the study recommended investigating the integrated corridor management between the ramp meters and the traffic signals on the surface streets. | | | | | |
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Development of an Optimal Ramp Metering Control Strategy for I-12

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October 2015

ABSTRACT

This study presents a comprehensive evaluation of various adaptive ramp metering strategies in order to identify the optimum algorithm that can help improve traffic conditions on I-12, Baton Rouge, Louisiana. The evaluated ramp metering strategies included the ALINEA local ramp metering control and mixed strategies case which included HERO coordinated and the local ALINEA control. The coordination was performed between three sets of two on-ramps, one on the eastbound and two on the westbound, while the other on-ramps were operating as ALINEA. The different strategies were compared to the current ramp metering strategy that was fixed-time.

Geometric and traffic data were collected to build and calibrate a simulation model to be used to test the different ramp metering strategies. Comparative evaluation was then performed on the simulation results of the three strategies using three performance measures: travel time, speed, and vehicle hours travelled (VHT). The three measures were aggregated for the entire corridor and averaged for different sections on the corridor while each section was representing a ramp metering location. The evaluation was conducted separately for the eastbound and westbound directions.

For the eastbound direction, the average travel time reduction was 2 seconds for ALINEA and 6 seconds for the mixed strategy case. For the travel speed, the average increase in speed was 0.2 mph for the ALINEA control and 0.4 mph for the mixed strategy. For the VHT, the average reduction was 2.5 veh.hrs for the ALINEA control and 6.5 veh.hrs for the mixed strategy case. On the other hand, for the westbound direction, the results showed more significant improvements. The average travel time reduction increased to 20 seconds for ALINEA control and 40 seconds for the mixed strategy case. For the travel speed, the average increase in speed was one mph for the ALINEA control and 2 mph for the mixed strategy. For the VHT, the average reduction was 195 veh.hrs for the ALINEA control and went up to 197 veh.hrs for the mixed strategy case. The statistical analysis on these results showed that while the improvements were not significant for the eastbound, they were significant for the westbound direction. Yet, most of the results were not considered practically significant. Therefore, more detailed section-by-section analysis was performed using the calculated performance measures for each section on the corridor.

The section-by-section analysis showed that none of the eastbound sections experienced any significant improvements. Whereas, on the westbound direction, three sections experienced significant improvements in the different performance measures: Range-O'neal, O'neal-

Millerville, and Millerville Sherwood. The travel time reductions on these sections were as high as 45 seconds and 30 seconds for ALINEA and the mixed strategies, respectively. The increase in speed was 9 mph and 13 mph for ALINEA and the mixed strategies, respectively. For the VHT, both strategies achieved reductions that reached 100 veh.hrs for the three sections. When the ALINEA and mixed strategies were compared to one another, the mixed strategy showed more significant improvements.

In summary, the eastbound did not experience any significant improvements in the traffic conditions. This is expected since this direction is operating at free flow conditions with the fixed-time strategy. On the other hand, for the westbound directions, the mixed strategy improved the traffic conditions significantly compared to the other control strategies. Yet, the achieved improvements were not as significant as expected. This was caused by the spillbacks at the off-ramps resulting from the vehicles waiting at the red traffic signals on the surface streets. Therefore, the study recommended investigating the integrated corridor management between the ramp meters and the traffic signals on the surface streets.

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IMPLEMENTATION STATEMENT

Ramp metering with fixed time control was implemented in June 2010 on I-12 in Baton Rouge between Essen Lane and Walker South Road/LA 447 from June to November 2010. The main objective was to reduce the frequency of breakdowns and improve the operational efficiency of traffic. The ramp metering is operated with a fixed cycle length (2 seconds of green/2 seconds of red) during the morning peak hours (6:00 to 9:00 AM) for the westbound traffic and during the evening peak hours (3:00 – 7:00 PM) for the eastbound traffic. A recent evaluation of the effectiveness of the ramp metering strategy concluded that the fixed time operation of the control system did not yield significant reductions in congestion along the corridor. This report presents findings of the evaluation of the effectiveness of a local responsive ramp metering strategy and a coordinated ramp metering strategy. The findings of this report provide an objective assessment of the benefits of the adaptive ramp metering strategies on I-12 to the officials of LADOTD and other interested transportation officials within Louisiana. Based on the reported findings of this study, recommendations were made to consider using the adaptive strategies. In addition, the study recommends investigating the integrated corridor management between the ramp meters and the traffic signals on the surface streets at the end of the off-ramps.

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INTRODUCTION

Urban freeways in major cities in the U.S. are operating near or beyond capacity conditions during peak periods due to increased travel demand. Such conditions often result in traffic breakdowns and heavy congestion, which continue to escalate and spread over the surface transportation network in the U.S. The transportation community of practitioners, researchers, and public agencies now recognizes the need for better management of the existing network capacity as a viable alternative to capacity expansion projects. In recent years, more emphasis has been placed on Active Traffic Management (ATM) strategies such as ramp metering, speed harmonization, managed lanes, and others. Ramp metering is one of the successful active traffic control strategies to control the flow of traffic entering the freeway facility from on-ramps and reduce the occurrence of breakdowns at merging areas by preserving the maximum traffic flow on the mainline. Optimal ramp metering control helps reduce the breakdown probability at merging locations, which is typically caused by a sudden influx of traffic from the on-ramp attempting a forced merge with mainline traffic.

From June to November 2010, LADOTD deployed ramp metering control, using a simple pre-timed operation with a fixed cycle length (2 seconds of green/2 seconds of red), along a 15 mile section of the I-12 in Baton Rouge, Louisiana. Ramp metering was implemented to reduce congestion, provide a safer merge operation at freeway entrances and improve travel time reliability of the corridor. A recent evaluation study for DOTD showed slight improvements in traffic conditions at some locations with fixed time ramp meters. Other locations exhibited no improvements or deterioration in traffic conditions, which may be attributed to the construction work on I-12 at some locations at the time of analysis and/or the inability of the fixed time ramp metering strategy to cope with the varying demand on the mainline. Therefore, the study recommended further investigation to examine the feasibility of applying dynamic ramp metering algorithms on I-12, wherever applicable. Demand responsive and coordinated ramp metering strategies involve a system where the signals change every few seconds in response to freeway conditions locally or at adjacent interchanges. The signals may work as individuals or coordinated clusters to resolve complex traffic problems and reduce congestion along the freeway. In either case, the dynamic control of the signals is feasible through Freeway Control Regulators (algorithms) that tend to optimize the capacity of the freeway.

The objective of this study was to conduct a comprehensive evaluation of various ramp metering strategies in order to identify the optimum algorithm that can help improve traffic conditions on I-12. The analysis included the performance of the current fixed time ramp

meters after the construction work was completed on I-12, in addition to the other ramp metering control strategies. The evaluation of performance for each ramp metering strategy was conducted using a microscopic simulation platform.

Ramp Metering Algorithms

Advanced Traffic Management (ATM) strategies such as ramp metering aim to improve the operation and safety of traffic by regulating the demand from on-ramps to the freeway mainstream. Also, such strategies are cost-effective, utilize existing infrastructure, and require minimal expansion to alleviate congestion in the region (1). In 1960, ramp meters were implemented for the first time in Chicago, Detroit and Los Angeles areas (2). Since that first implementation, transportation researchers started to investigate different operational strategies in order to optimize the performance of ramp meters. For fixed-time metering strategies, ramp meter timings are adjusted automatically by specified time-of-day parameters. This algorithm does not afford flexibility for changing traffic conditions. Traffic-responsive ramp metering strategies, as opposed to fixed-time strategies, are based on real-time measurements from sensors installed in the freeway network and can be classified as local or coordinated. Local control is a process of selecting ramp meter rates based solely on conditions present at an individual ramp, while coordinated control is a process of coordinating the metering rates for group of ramps based on conditions throughout the entire length of the metered corridor.

In general, for a ramp controlling methodology to be ideal, it should be able to describe both the operations and control in the freeway system accurately, possess theoretical foundation, proactive, balanced, accurate, robust, computationally efficient, flexible, expandable, able to handle special situation and simple (3).

Local Ramp Metering Strategies

Local ramp metering strategies are those incorporating the traffic parameters only within the vicinity of the On-ramp to calculate the optimal on ramp flow rate. This section reviews the common local ramp metering algorithms developed.

Masher (4) developed a Demand-Capacity (DC) ramp metering algorithm, which is a traffic responsive algorithm that measures the downstream occupancy. If it is above the critical occupancy, congestion is assumed to exist. The metering rate is then set to the minimum rate.

Otherwise, the volume is measured upstream of the merge, and the metering rate is set to the difference between the downstream capacity and the upstream volume.

The occupancy (OCC) strategy is an occupancy-based feed forward strategy, which is even more inaccurate than the DC strategy due to the linearity assumption for the fundamental diagram and the uncertainty (5). This strategy uses only upstream sensor occupancy measurements to identify and measure congestion. The critical occupancy is measured using historical data.

Both the DC and OCC are considered open-loop systems. In such systems the output from the system is not used as input for the next iteration. These systems are unreliable due to the lack of feedback mechanism (6), unlike the Asservissement Linéaire d'Entrée Auotrouitière (ALINEA) algorithm proposed by Papageorgiou (7). The ALINEA is a local responsive feedback ramp metering strategy, which has had multiple successful field applications (Paris, Amsterdam, Glasgow, and Munich). This algorithm considers traffic flow as the process being controlled and the metering rate as the control variable. Based on the feedback control theory, the algorithm attempts to set the metering rate such that traffic flow will not exceed system capacity. The algorithm uses the difference in occupancy values (desired or capacity versus measured), measured at a point 12 feet downstream of the ramp gore, to calculate a metering rate. One of the most desirable features of this closed loop algorithm is the integration of the previous time interval metering rate within the equation. This allows integrated smoothing of the metering rates to avoid wide swings between concurrent time intervals. The ALINEA algorithm is easy to implement because of the minimal requirements. However, it does not consider queue spill-back directly, which is generally handled through overriding restrictive metering rates, and would have difficulty to balance freeway congestion and ramp queues when traffic becomes heavily congested (3).

In another paper, Smaragdis (6) presented several modifications and extensions of ALINEA. Specifically, FL-ALINEA is a flow-based strategy; UP-ALINEA is an upstream occupancy-based version; UF-ALINEA is an upstream-flow-based strategy. X-ALINEA/Q is the combination of any of the above strategies with efficient ramp-queue control to avoid interference with surface street traffic.

A zone algorithm was reported as used in Minnesota (8). This algorithm defines directional freeway facility “metering zones” with zones having variable lengths of three to six miles. The basic concept of the algorithm is to balance the volume of traffic entering and leaving each zone. All entering and exiting traffic volumes on both the mainline and the ramps are

measured in 30-second increments, and balancing these total volumes is used to keep the density of traffic within the zone constant.

Ghods (9) proposed an adaptive genetic fuzzy control approach to reduce peak hour congestion, along with speed limit control. To calibrate the fuzzy controller, a genetic algorithm is used to tune the fuzzy sets parameters so that the total time spent in the network remains minimum. The proposed method is tested in a stretch of a freeway network using a macroscopic traffic model in an adaptive scheme.

Ozbay (10) developed an isolated feedback-based ramp-metering strategy that takes into account the ramp queue. In addition to the regulation of ramp input, the strategy calls for regulation of ramp queues by explicitly incorporating them into the model. This isolated ramp-metering strategy is tested using PARAMICS, a microscopic traffic simulation package, on a calibrated test network located in Hayward, California. The strategy was found to be effective in optimizing freeway traffic conditions (reduction in mean congestion duration on the freeway downstream link, mean downstream occupancy, and travel time).

Coordinated Ramp Metering Strategies

Unlike local ramp metering strategies, coordinated strategies account for the traffic conditions at a set of consecutive ramps. Coordinated ramp metering strategies have been suggested as more effective than local ramp metering especially when there are multiple congestion bottlenecks on the freeway, excessive ramp delays, and when the performance optimization of freeway and on-ramps requires the metering of several ramps. Many coordinated strategies were developed using different controlling parameters. In this section, different strategies are reviewed.

The bottleneck metering algorithm is a system ramp control, which includes several internal adjustments of a volume reduction based on downstream bottlenecks and localized adjustments, such as queue override (11). At the local level, historical data is used to determine approximate volume-occupancy relationships near capacity for each ramp location. Local metering rates are then calculated to allow ramp volumes to equal the difference between the estimated capacity and the real-time upstream volume. The coordinated bottleneck algorithm is activated when the following two criteria are met: (1) downstream bottleneck-prone section surpasses a pre-determined occupancy threshold, and (2) the “zone” or area of influence upstream of the bottleneck is storing vehicles. The algorithm then uses centrally assigned metering rate reductions applied to meters in the zone

to reduce the number of vehicles entering the mainline by the number of vehicles stored in the bottleneck area of influence.

ARMS (Advanced Real-time Metering System) consists of three operational control levels within a single algorithm: free-flow control, congestion prediction, and congestion resolution (12). Flow is treated as a semi-static process in which traffic flow varies slowly with time, where the control decisions are based on a free flow model. Congestion prediction works to predict (and thus pre-empt) traffic flow breakdowns caused by dynamic traffic fluctuations. Traffic flow is modeled as a rapidly changing dynamic process. Combining this control module with the free-flow control module provides for an environment in which the probability of congestion occurring is reduced. Congestion reduction is a dynamic algorithm that balances congestion resolution time and metering rates by integrating both freeway and surface street operations. This algorithm has been successfully tested in simulation models.

Wei (13) developed a coordinated metering algorithm using artificial neural networks. This algorithm is based on an Artificial Neural Network (ANN) with a “learning” capability. It is used in an offline capacity to generate an initial, preliminary metering plan, which is used within a back-propagation algorithm to “train” the neural network. The roadway system is divided into control zones, and input data for the algorithm is collected at each ramp in a zone, V/C ratios upstream and downstream of the ramp and the ramp queue length on each ramp. As the metering rate for each on-ramp is affected primarily by the mainline V/C measurements near the ramp and only partially by the traffic conditions elsewhere in the zone, a partially connected neural network is used.

The internal model tracks the actual traffic conditions, the implemented control strategies, and the results. This information is evaluated and, if necessary, additional self-adjustment training data is provided for the ANN system until the desired traffic condition is reached.

Seeking to address the interaction of the freeway system with the adjacent surface-street system, Gettman (14) presents a multi-objective integrated large-scale optimized ramp metering system for freeway traffic management. This was done by providing a method to trade-off queue growth at individual ramps in a freeway corridor. The system is composed of three primary components: area-wide metering rate coordination, predictive-cooperative real-time rate regulation, and anomaly detection/optimization scheduling. The area-wide rate coordination algorithm is based on a multi-criteria quadratic programming problem. The predictive-cooperative real-time rate regulation algorithm is a pro-active approach to local traffic-responsive control using “scenario based” linear programming. Re-optimization

intervals of the area-wide coordination and the predictive-cooperative real-time rate regulation algorithms are scheduled by a process monitoring function based on concepts in statistical process control. The performance of the method was evaluated using a simulation test case for a typical three-hour peak period on a realistic freeway in Phoenix, AZ, in freeway average speed, total travel time, queue time, and congestion recovery time.

Zhang (15) developed a new freeway ramp control objective: minimizing total weighted (perceived) travel time, which is presented in this study. This new objective function is capable of balancing efficiency and equity of ramp meters, while the previous metering objective, minimizing total absolute travel time, is purely efficiency-oriented and hence produces a most efficient but least equitable solution. Consequently, a ramp control strategy BEEEX (Balanced Efficiency and Equity) was developed. BEEEX seeks to minimize the total weighted travel time, which involves weighting both the freeway mainline travel time and the ramp delays.

A ramp metering algorithm incorporating “fuzzy logic” decision support was developed at the University of Washington (16). This algorithm was installed in early 1999 by WSDOT, controlling 15 metered ramps along I-405. The algorithm, based on fuzzy set theory, is designed to overcome some of the limitations of existing conventional ramp metering systems. In a simulation based evaluation using FREeway SIMulation (FRESIM) and a model of the Seattle I-5 corridor, the fuzzy controller demonstrated improved robustness, prevented heavy congestion, intelligently balanced conflicting needs, and tuned easily. The objective was to maximize total distance traveled, minimize total travel time and vehicle delay, and still maintain acceptable ramp queues. This algorithm functions on two levels and provides both local and downstream bottleneck metering rate selection.

A freeway traffic control system has been in place on the Hanshin Expressway near Kobe, Japan. The Hanshin algorithm is based on Linear Programming formulation (17). The linear algorithm maximizes the weighted sum of ramp flows. It also computes a real-time capacity for each road segment. The algorithm requires a very comprehensive data collection system with detectors closely spaced on the mainline and multi-point detection on all exit/entrance ramps. To solve for metering rates, the algorithm uses both real-time and pre-defined system variables as well a number of tuned parameters and weighting factors for a series of ramps. The performance of the algorithm is heavily dependent on accurate origin-destination data.

Another coordinated ramp metering strategy, METALINE, is a coordinated generalization (using lists of multiple values, or columnar vectors, in place of single values) of ALINEA

(18). The metering rate of each ramp is computed based on the change in measured occupancy of each freeway segment and the deviation of occupancy from critical occupancy for each segment that has a controlled on-ramp. This algorithm incorporates a smoothing feature from the ALINEA algorithm, preventing wide swings in metering rates between concurrent time intervals by incorporating the previous metering rate into the equation for calculating the next time interval metering rate. The sensitivity of this algorithm is also quite high, as it responds to the change in occupancy between time intervals, rather than the overall occupancy of the system, allowing more responsive operation for smaller changes in traffic flow.

Chang (19) proposed a metering model for non-recurrent congestion. This algorithm uses a two-segment linear flow density model. Kalman filtering and auto-regressive moving average techniques are used for estimating link densities and ramp queue lengths from point volume and occupancy detector data and traffic system model parameters. A dynamic equation for density evolution, according to the flow conservation law, is formulated to describe the freeway traffic system and ramp traffic dynamics. The traffic evolution equations act as the essential constraints for optimizing metering rates. Other constraints are the lower and upper physical bounds on the mean link densities, the maximum and minimum allowable metering rates, and the maximum allowable ramp queue length. Traffic flow or throughput is then solved for within the objective function using linear programming mathematics.

As the successor of the ZONE metering algorithm, the Stratified Zone Ramp Metering (SZM) Strategy has been developed and deployed in the Minneapolis/Saint Paul area (20). The SZM strategy aims in maximizing freeway throughput while keeping ramp waiting times below a predetermined threshold. It focused on a better determination of the minimum release rate for each ramp and its integration with the overall SZM strategy. The SZM strategy is tested in two freeway sites under various demand scenarios through a state-of-the-art microscopic simulator. The simulation results indicate that the SZM strategy is effective in delaying and decreasing the freeway congestion as well as resulting in smoother freeway traffic flow.

In a recent study, Papamichail (21) developed a traffic- response feedback control strategy, HERO (Heuristic Ramp Metering Coordination), to coordinate local ramp metering actions in freeway networks. In the framework of HERO, ALINEA ramp metering strategy was applied to each on-ramp, the desired ramp flow was calculated, and the ramp queue was estimated. The coordination using HERO was materialized via occasional appropriate setting

of minimum ramp-queue lengths that should be created and maintained at specific ramps. A pilot project of HERO has been implemented in Melbourne, Australia, as a part of the Monash-Citylin-West Gate (MCW) upgrade. Another HERO strategy implementation took place on the M1/M3 freeway in Queensland, Australia. Faulkner (22) investigated the impact of HERO on the performance of the freeway and found that the traffic throughput and travel times improved significantly compared to the fixed-time ramp metering strategy.

Wang (23) proposed an area-wide ramp metering system to improve the coordination of ramp meters for system-wide optimization and on-ramp overflow minimization. It uses the principles of a computer network congestion control strategy, which reduces certain types of congestion at a targeted freeway location through limiting on-ramp vehicle flows to a fraction of ramp demand and then additively increasing rates to avoid ramp queue spillover onto city streets. The effectiveness of this ramp metering approach has been evaluated by microscopic simulation experiments.

Kwon (24) introduced a density-based adaptive ramp metering strategy. The new strategy is based on a 'segment density' and adopts an implicit coordination approach in determining the rates of each meter to manage the flows at bottlenecks. The new algorithm is coded with the Java language and incorporated into the current version of Intelligent Road Information System (IRIS). IRIS is a computerized operating system developed by the MnDOT to operate field devices such as ramp meters. Then, this metering algorithm is evaluated with the IRIS-in-Loop simulation system (ILSS), which has been equipped with the new metering module as described above. The proposed algorithm showed significant reduction of the delayed vehicle hours and lost vehicle miles traveled because of congestion, while maintaining similar or slightly higher values of the total vehicle miles traveled than the current metering method. The speed contours also show the reduced congestion level throughout the test corridor, which includes multiple bottlenecks because of the relatively short ramp-to-ramp distances.

Recently, Torne (25) proposed a coordinated ramp metering strategy with Dynamic Speed Limits. This strategy is based in a formulation which captures the endogenous merge capacity. They performed a cell transmission model extension. This strategy reduces the capacity drop occurrence in the vicinity of an on-ramp. Results show improvement in the performance indicators of the system such as total travel time spent (TTS), speed, flow, density and ramp queue length.

Another research on HERO and ALINEA algorithms is by Li (26). They combined previous methods with Variable Speed Limit (VSL) for a critical bottleneck section of Auckland Motorway using AIMSUN micro-simulation. Results presented that HERO combined with VSL control strategy has outperformed all other control strategies.

Ramp Metering Evaluation Studies

Similarly, several studies have been conducted to evaluate the overall benefits of ramp metering in terms of throughput, travel speeds, and travel times on the mainline. For instance, Bhourri and Kaupplia (27) evaluated the travel time reliability benefits of ramp metering based on a study of a segment of the French motorway A6W, which comprises five on-ramps and lasts for 20 kilometers. The study applied four different ways to measure the travel time reliability: statistical range methods, buffer time methods, tardy trip measures, and probabilistic measures. The study concluded that different reliability measuring methods lead to inconsistency of results, and that in order to reach the optimal policy solutions, the benefits from improvement of average travel time and from improvement of travel time reliability need to be separated.

Washington State Department of Transportation (WSDOT) reported in a study (2012) that ramp meters reduced the risk of merging accidents on several of its major highways and freeways. Similar safety observations, attributed to ramp meters, have been made by the Georgia Department of Transportation (2010), and the California Department of Transportation (2000). Another practical case showing evidence of the merits of ramp metering is that of the Twin Cities in Minnesota, which had 430 active ramp meters turned off during the fall of 2000 due to the public questioning its effectiveness. The results were a decline in through traffic by 14%, a doubling of travel time unpredictability, and a 26% increase in crash rate which was the equivalent of 1,041 crashes per year (2001).

Lee (28) applied a real-time crash prediction model (CPM) to investigate the safety benefits of a local traffic-responsive ramp metering control (ALINEA) on freeway. Safety benefits were measured in terms of reduced crash potential, estimated by CPM. Traffic flow changes were captured by a microscopic traffic simulation model. The study concluded that ALINEA ramp metering control could reduce 5%-37% crash potential over the no-control case. Particularly, the crash reduction was most noticeable under the condition when congestion was caused by a high ramp traffic volume without a queue at downstream ramp.

Wu (29) investigated the impacts of ramp metering on driver behaviors in South England. The research studied the performance of drivers on ramps and on motorway carriageways with and without ramp metering. The study concluded that ramp metering didn't have significant impacts on passing traffic in terms of speeds, headway, accelerations, and decelerations. The ramp metering caused increased lane changes in pre-merge zones and thus resulted in changes of speeds and headways in pre-merge passing traffic.

In 1999, WSDOT evaluated its Renton Ramp Meters at nine locations on the I-405 (2000). Travel times and speeds were manually recorded by drivers traveling the study corridor for two weeks before and three days after the ramp meters were activated. The days chosen for evaluation were Tuesdays, Wednesdays, and Thursdays. Travel speeds, recorded at checkpoints, were averaged between checkpoints to represent segment speeds. No statistical analysis was made because of the limited number of trials. The results showed that ramp meters effectively increased speeds by 7 to 20 mph, and provided travel time savings of 3 to 16 minutes, depending on the time of day.

Zhang (30) tested the effectiveness of ramp metering for several representative freeways in the Twin Cities during the afternoon peak period. Seven performance measures were used to compare conditions with and without ramp metering, including mobility, equality, travel time variation, travel demand responses, etc. The study concluded that ramp metering was more helpful for long trips than short trips. Ramp metering reduced the travel time variations yet did not improve trip travel time due to ramp delays. Work-trips and non-work trips responded differently to the ramp metering control.

Zhang and Levinson (31) studied the traffic flow characteristics at twenty-seven active bottlenecks in the Twin Cities for seven weeks with and seven weeks without ramp metering to determine whether ramp meters increase the capacity of active freeway bottlenecks. The authors developed a series of hypotheses concerning the relationship between ramp metering and the capacity of bottlenecks and tested the hypotheses against real traffic data. The results showed that ramp metering could increase capacity by postponing or eliminating bottleneck activation, accommodating higher flows during the pre-queue transition period than no-control, and increasing queue discharge flow rates after breakdown.

In the assessment of the Twin Cities ramp meters in 2000, the Minnesota Department of Transportation (2001) focused on three parameters: travel time, travel speed (both collected with GPS equipped vehicle), and traffic volume (collected by loop detectors). Data was collected over a five-week period when ramp metering was activated, and another five-week

period when ramp metering was deactivated. Statistical tests showed there were no differences between the different weekdays as well as between the different weather conditions. As such, all valid observations were grouped and analyzed together. The results showed that travel speeds on the freeway mainline improved with ramp metering by an average 7.4 mph. The Freeway throughput increased by 9% on average and 14% during peak hours. The ramp meter system provided an annual saving of 25,121 hours of travel time.

Ishak (32) in one study applied fixed rate ramp metering strategies on the two corridors of I-10 and I-12 within the city of Baton Rouge in order to determine their effectiveness in integrated corridor management to reduce congestion on the freeway and arterial systems in Baton Rouge. Traffic data from the City of Baton Rouge Regional Planning Council and geometric data were collected. A Friction Factor Matrix was created to determine the origin-destination flows for the morning peak period. The simulation platform used in this study is VISSIM version 5. A set of network-level performance measures was also identified as: Average delay, Average number of stops per vehicles, Average speed, Average stopped delay per vehicle, Total delay time, Total Distance Traveled, Number of Stops, Total stopped delay, and Total travel time. Comparative evaluation and statistical analysis of the identified performance measures for both metered and non-metered traffic had been done. Based on the results, the study recommends the use of ramp metering on both segments of I-10 and I-12.

Lu (33) reached to this point that it is necessary to coordinate all the important entrance ramps (with high demand) and relevant arterial intersections along a freeway corridor in their research project. The objective of this project was to develop and test a practical coordination strategy between a freeway entrance ramp meter and an arterial intersection traffic signal. They developed a generic algorithm for the coordination of intersection traffic signal and freeway ramp metering. They used ALINEA algorithm to achieve local adaptive ramp metering. The coordination strategy of the two traffic control system was formulated as adjusting some parameters in the objective function of the optimization procedure. Two approaches heuristic and system-wide optimization. A microscopic simulation model was built in Aimsun in order to evaluate the performance of the proposed control method. The limited field operational test was conducted including development of hardware and software systems, communication interface, control algorithm, and data flows. For success of field test, a progressive system implementation and field test procedure were applied. This field test proved to be very effective to avoid any significant negative impact on traffic which could be very sensitive.

The review of the literature indicated that for specific networks layouts as limited ramp storage for the on ramps and under certain traffic conditions as multiple bottlenecks on the freeway, the coordinated ramp metering strategies can provide better utilization of the freeway capacity compared to the local ones. Local ramp meters will respond to limited ramp storage for a ramp by providing excessive queue overrides on that ramp causing increased congestion at the freeway, on the other hand coordinated strategies will coordinate with other nearby ramps having sufficient storage available by decreasing their ramp flow rates to compensate for the ramps undergoing shortage in storage length. However, the effectiveness of the coordinated strategies, to outperform local ones, depends on many variables as the number of the coordinated ramps, the relative distance between them, and location of the bottleneck relative to them. As a result, the network in this study was simulated for both responsive strategies, the local and the coordinated ramp metering strategy. The review of the literature showed a consensus about the ALINEA being one of the most effective local strategies. That is due to the ALINEA being a feedback control scheme targeting a critical occupancy value which believed to be constant from day to day. Unlike other local strategies targeting critical capacity values that vary from day to day leading to underutilization or congestion for the freeway. As result, the ALINEA was selected as the local ramp metering strategy for the network. However, there is no such consensus in the literature for a specific coordinated strategy, perhaps due to the limited application of these strategies in reality. Since the HERO algorithm is just a coordination of several ALINEA ramps, it was adopted for the coordinated ramp metering strategy. The fact that the HERO strategy is based on the ALINEA makes the upgrade for a number of ramps from ALINEA to HERO feasible and cost effective for the control units and the control algorithms compared to any other coordinated strategy.

OBJECTIVES

The proposed research will identify the optimal ramp metering control strategy and the anticipated operational benefits over the existing fixed time strategy. A traffic simulation tool will be used to model the existing traffic conditions on I-12 corridor, using collected and calibrated traffic data. The most suitable algorithms to the conditions on I-12 will be tested to find the optimal one that is capable of optimizing traffic throughput, travel time reliability and delays on the mainline. Based on the results, the optimal strategy may be tested in the field over a short period of time before the implementation recommendation is made. More specifically, the specific objectives of this phase of research are to:

1. Review the state of the practice of the different ramp metering strategies and applications in other metropolitan areas in order to learn from similar experiences and identify points of strengths and weaknesses of the various strategies. This includes identification of the ramp metering strategies that were proved to be effective to improving traffic conditions in similar study areas as I-12.
2. Identify and collect the geometric and traffic data required to simulate the I-12 corridor under the selected ramp metering strategies.
3. Select a microscopic simulation platform and build the simulation network for the study corridor.
4. Calibrate the selected simulation model with the collected data to replicate the actual traffic conditions on the study corridor.
5. Identify a set of parameters and performance measures for the ramp metering strategies. Examples include travel time, delay, throughput, etc.
6. Conduct and analyze the results of multiple runs for each of the selected ramp metering strategies with different traffic demand scenarios in order to minimize the probability of breakdowns along the corridor.
7. Make final recommendations based on the main findings of the study.

SCOPE

The research is restricted to developing and testing ramp metering strategies for Interstate I-12 in Louisiana using a traffic simulation tool. Interstate highways are defined as control-of-access facilities under the federal-aid jurisdiction. The research will identify the optimal ramp metering control strategy and the anticipated operational benefits over the existing fixed time strategy.

STUDY AREA

A total of 14 ramp meters were installed in 2010 along the 15.7 mile corridor of I-12 in Baton Rouge, Louisiana, between Essen Lane and Walker South Road/LA 447. Figure 1 shows the locations of ramp meters. The figure shows 5 ramp meters for the eastbound direction and 9 ramp meters for the westbound direction. Since this was the first time ramp metering control was adopted in Louisiana, a simple pre-timed operation with a fixed cycle length was used. During weekdays, the meters are turned on during the AM peak period (6:00 a.m. – 9:00 a.m.) for westbound traffic, and during the PM peak period (3:00 p.m. – 7:00 p.m.) for eastbound traffic. Queue override strategy is also used for the ramps. Using video detection, as vehicles spill back on the ramps until they reach the end of the ramp at the surface streets, the ramp meters are programmed to turn green until the queued vehicles are flushed.

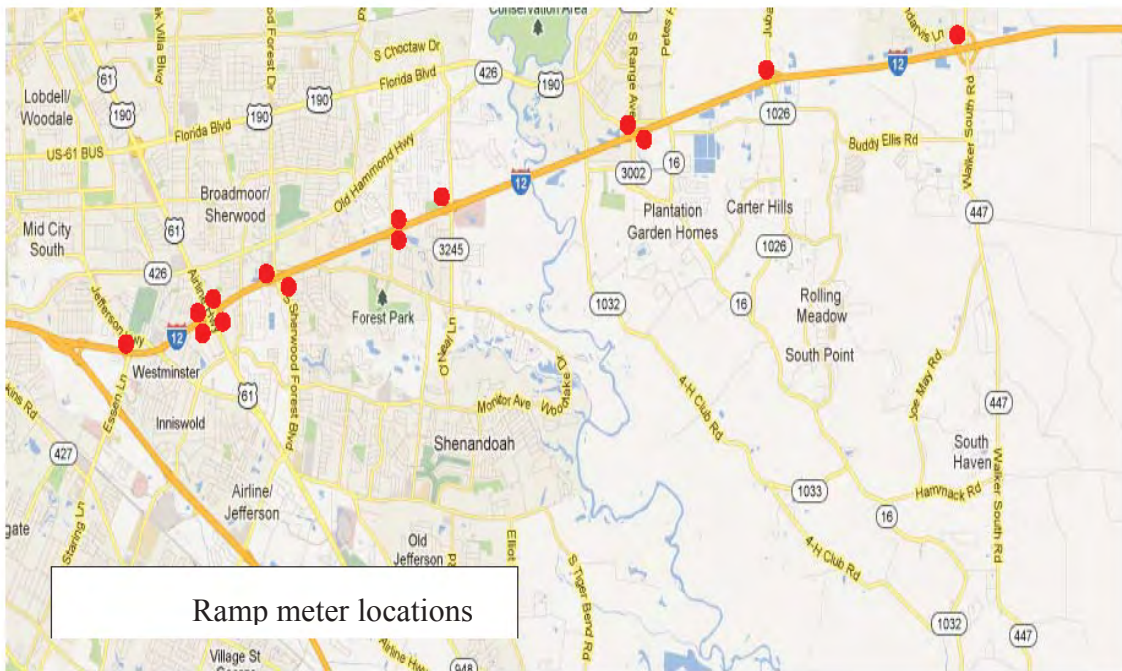


Figure 1
Study area and locations of ramp meters along the I-12 corridor

METHODOLOGY

The selected ramp metering strategies were tested using VISSIM microsimulation software that has been widely used in similar applications. Traffic simulation has been widely used because of its benefits compared to the in-situ implementation that has safety and economic concerns especially in the testing stage. The methodology of this research is depicted in Figure 2. First of all, geometric information about the study corridor was obtained from google maps. In addition, the traffic data including traffic volumes and speeds were collected from at the on-ramp and off-ramp locations over the ramp meters hours of operation. Using the geometric data, the I-12 corridor geometric network was encoded in VISSIM simulation software. Afterwards, the collected traffic data were used to calibrate the simulation model under the current fixed-time ramp metering strategy. As the I-12 simulation model is calibrated, the selected different ramp metering strategies were tested. Different performance measures were then calculated using the resulting simulation output to serve as an evaluation criteria. Using the calculated performance measures, a comparative analysis was performed between the different strategies in order to determine the optimal ramp metering strategy.

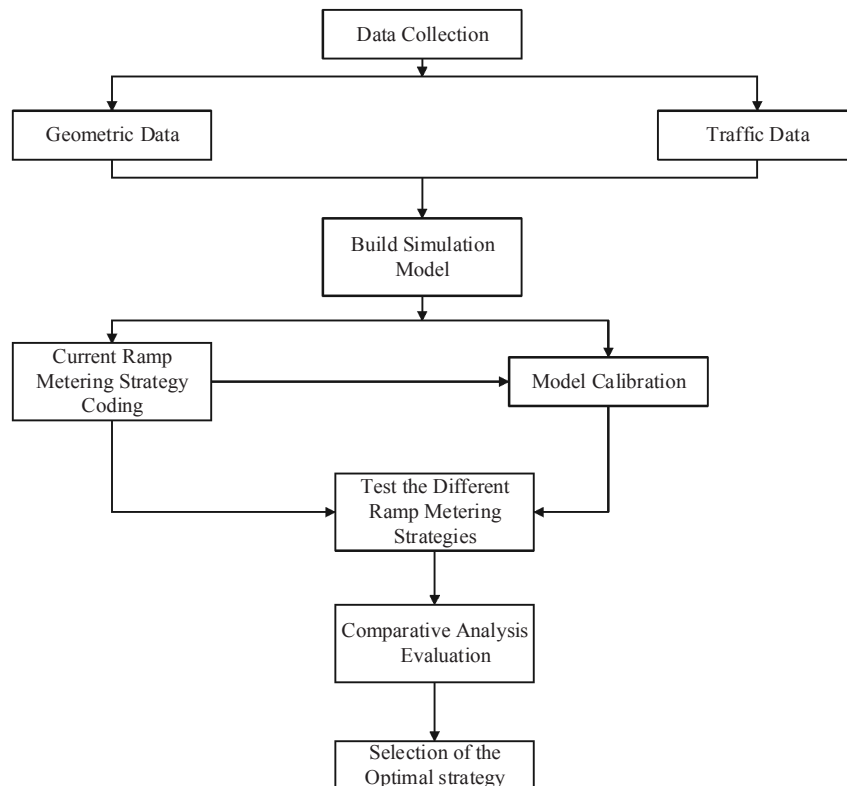


Figure 2
Research Methodology

Ramp Metering Strategy

Three different ramp metering strategies were simulated for the comparative analysis: (a) fixed time strategy, which represents the current ramp metering control strategy (b) a local feedback ramp-metering strategy (ALINEA), and (c) Mixed strategy, which included the heuristic traffic-responsive feedback control strategy (HERO) on some ramps and ALINEA on the rest of the ramps. The different strategies were encoded using the Vehicle Actuated Programming (VAP) interface of VISSIM and shown in Appendix A. The control methodology for the each ramp metering strategy is described in the following section.

Fixed Ramp Metering Strategy

The fixed time strategy is the current control scheme used to operate the I-12 on-ramps. The ramp meters are set up to account for a 2 seconds of green followed by a 2 seconds of red time. When there are no vehicles waiting on the on-ramps to enter the mainline, the signal is set to remain red. As the vehicles start to arrive, a call is sent to the signal controllers from the presence detectors placed on the ramps so that the signal starts to turn green. During each of the fixed 2 seconds of green only one vehicle is allowed to enter the I-12 mainline.

Queue override strategy is used in addition to the fixed-time ramp control strategy. Queue detectors are placed at the end of each ramp so that, as the ramp queues reach the detector locations, the ramp meter traffic signal turn to continuous green to flush the ramp queues.

Local Traffic Responsive Strategy: ALINEA

Local traffic responsive strategy (ALINEA) is a dynamic, local, and closed loop measure strategy that reflects the variation in the mainline and ramp volumes. ALINEA estimates the metering flow rate based on the difference between the actual downstream traffic occupancy and a desired occupancy value that is assigned by the designer. The ramp flow value $r(k_c)$ for each predefined time step k_c is determined by,

$$r(k_c) = r(k_c - 1) + K_R[\hat{O} - O(k_c - 1)] \quad 1)$$

Where , $r(k_c)$ and $r(k_c - 1)$ are the ramp metering flow rates for the current and the previous time steps, K_R is a regulator parameter that is recommended to be set to 70 veh/hr, \hat{O} is the desired downstream occupancy, and $O(k_c - 1)$ is the downstream occupancy measured at the previous time step. Using the ramp metering flow rate, the signal timing is updated using the following equation:

$$RedInterval(k_c) = \frac{3600}{r(k_c)} \cdot Number\ of\ Metered\ lanes - GreenInterval \quad (2)$$

As the downstream conditions improve, defined by an actual occupancy less than the desired value, the ramp flow rate increases. This means that more vehicles can be allowed to enter the mainline and hence the signal timing is updated to allow shorter red times and more frequent green intervals (each of 2 seconds of green). On the other hand, as the downstream conditions worsen, defined by an actual occupancy higher than the desired value, the ramp flow rate is decreased. In order to account for that, the signal timing is updated to allow longer red times and less frequent green intervals.

As the red times become longer because of congested downstream conditions on the mainline, queues start to form on the on-ramps that might spillback on the surface streets. In order to prevent that from happening, queue override strategy is used. Queue detectors were placed at a distance of 60 to 80% of the ramp length, to detect the ramp queues. The queue override strategy is set so that, as the ramp queue reaches the queue detectors' location with an occupancy value of 0.1, the ramp meter traffic signal turns to a continuous green until the ramp queue is flushed. The queue detectors distance was changed as the currently used case, the detectors at the very end of the on-ramps, may not help to prevent the surface streets queue spillbacks totally.

Heuristic Traffic Responsive Feedback Control Strategy: HERO

Heuristic Traffic Responsive Feedback Control (HERO) is a coordinated ramp metering control strategy. The HERO strategy was performed between three sets of two ramps as shown in Figure 3. The selected locations were the only ramps that can be coordinated because of their vicinity to each other. The other locations are spaced apart which does not allow the coordination to be effective. HERO strategy coordinates the ramp meter flow rates on at least two successive on-ramps. In HERO strategy, the on-ramps are first controlled by ALINEA local strategy then as specific traffic conditions are satisfied on the mainline and the on-ramps, the coordination is activated. Figure 4 shows the ramp metering control scheme in HERO or mixed strategy.

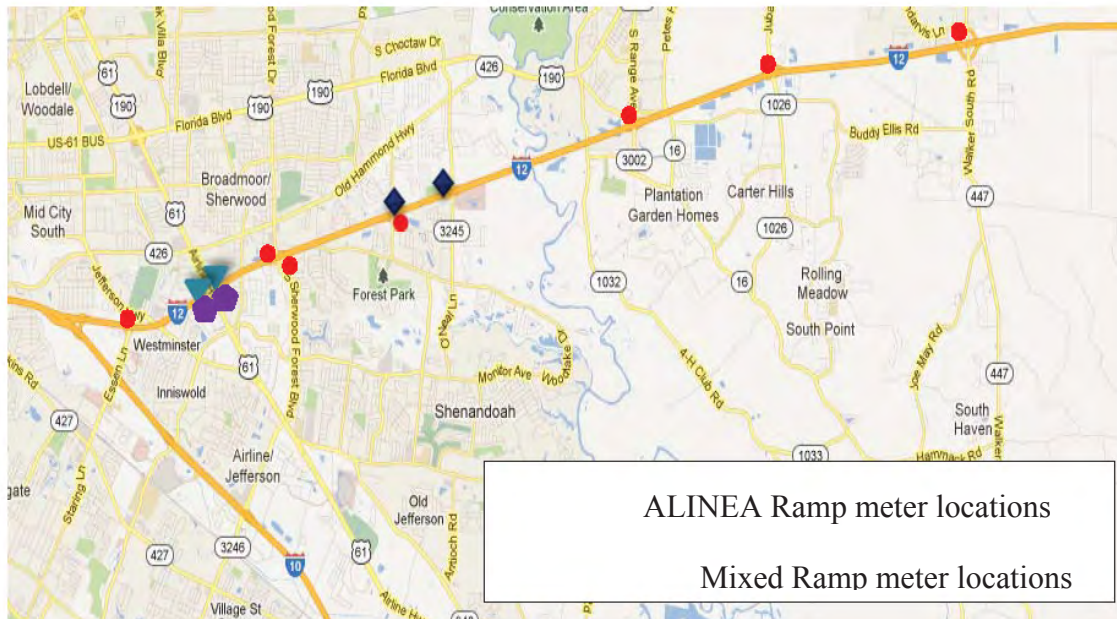


Figure 3
Locations of ramp metering coordination

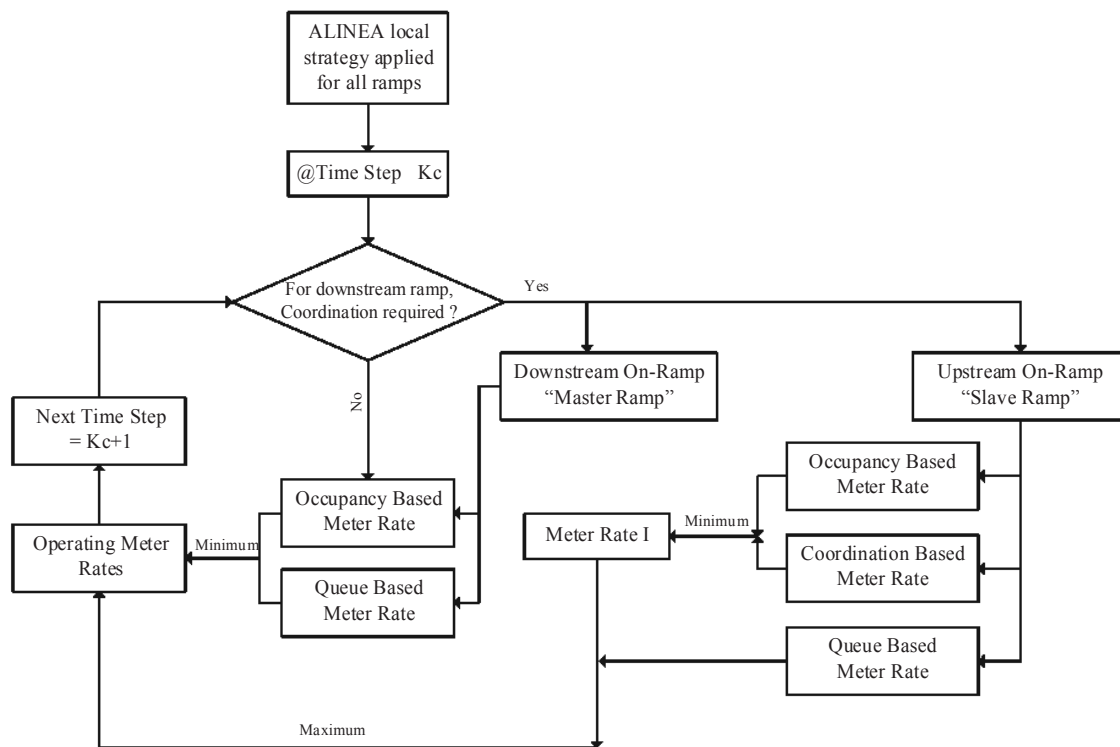


Figure 4
Operation process for mixed ramp metering algorithm

As shown in the figure, the two ramps (where coordination is required) start operating with ALINEA local strategy. The meter flow rate for ALINEA, in the mixed strategy, is calculated as the maximum of two values. The first meter rate is calculated based on the downstream conditions as in equation 1. Whereas, the second meter rate is calculated so as to ensure that the queue length on any ramp does not exceed a predefined maximum value. This is calculated by

$$r(k_c) = -\frac{1}{T_c} [w_{max} - w(k_c)] + d(k_c - 1) \quad (3)$$

where, T_c is length of the feedback control time steps, w_{max} is the maximum allowed queue length on the ramp, w_o is the actual ramp queue length, and d is the ramp demand.

Continuously, at the end of each feedback control time step, the traffic conditions downstream the downstream on-ramp as well as on the downstream on-ramp are checked against the thresholds in the following equations:

$$\frac{w_d}{w_{max}} > \text{Maximum threshold} \quad (4)$$

$$O > 0.9 * \hat{O} \quad (5)$$

where, w_d is the actual queue length on the downstream ramp, w_{max} is the maximum allowed queue length on the downstream ramp, O is the actual occupancy downstream the merging area of the downstream ramp, and \hat{O} is the desired occupancy downstream the merging area of the downstream ramp. If the two conditions are satisfied, the coordination between the two ramps is activated with the downstream ramp treated as the master ramp and the upstream ramp treated as the slave ramp.

For the master ramp, ALINEA rules remain in operation; whereas, more restrictions are used for the meter rate of the slave ramp. The meter flow rate of the slave ramp is calculated in two steps. First, the meter rate is calculated as the minimum of the values obtained from equation 1 and the equation below

$$r_{lc}(k_c) = -\frac{1}{T_c} [w_{min} - w(k_c)] + d(k_c - 1) \quad (6)$$

where, w_{min} is the minimum permissible queue length on the slave ramp. The reason for maintaining a minimum queue on the slave ramp is to allow better traffic conditions at the merging area downstream the master ramp. This can help more vehicles to be discharged from the master ramp. Then, the final meter rate is calculated as the maximum of the values obtained from the first step and equation 4. The minimum permissible queue on the slave ramp is calculated based on the actual and maximum allowed queue values on both the slave and master ramp by

$$W_{min} = \frac{w_{slave}(k_c) + w_{master}(k_c)}{w_{max,slave} + w_{max,master}} \cdot W_{max,master} \quad (7)$$

While the coordination is active, the traffic conditions on and downstream the master ramp are checked for any improvements using the conditions in the following equations:

$$\frac{W_o}{W_{max}} < deactivated\ threshold \quad (8)$$

$$0 < 0.8 * \hat{O} \quad (9)$$

If these conditions are not satisfied, this means that the coordination is still required. Otherwise, the coordination is deactivated and each ramp starts to operate locally using ALINEA control strategy.

Measures of Performance

The three ramp metering strategies were evaluated using three performance measures: travel time, speed, and vehicle hours travelled (VHT). The three measures were obtained for each of the tested strategies with the fixed-time control considered as the base case. The different measures were obtained for 20 simulation runs for each strategy in order to account for the randomness effect in the simulation results. The average values over the simulation runs were obtained for each ramp meter location to be used for section-by-section analysis. In addition, the aggregated averaged measures obtained along the entire corridor to be used for corridor-level analysis. Then, comparative statistical analysis at 5% level of significance was performed on each performance measure to find the optimal strategy.

The Analysis Of Variance (ANOVA) was performed on each measure of performance over the different ramp metering strategies. This was performed for the calculated measure of performance along the corridor (corridor-level calculated measure of performance) to investigate whether changing the ramp metering strategy would improve that measure significantly. Then, if a significant improvement was found for the entire corridor, further section-by-section analysis was then performed using the measure of performance calculated for each ramp meter location (section-level calculated speed). The section-by-section analysis was performed to investigate the ramp meter locations that benefited the most from each strategy.

The following sections describe the methodology used to compute each measures of performance.

Travel Time

The freeway was divided into smaller segments where each segment includes an on-ramp meter location. For each segment, travel time measuring sections were placed in VISSIM simulation

models. The travel times for the different strategies were then measured for each vehicle and then the average value was obtained for each section. In addition, the average travel times were aggregated over the entire corridor. The calculations were performed over the ramp meters' periods of operation (6:00-9:00 AM, for the Westbound, and 3:00-7:00 PM, for the Eastbound).

Travel Speed

The travel speed for each vehicle was calculated using the measured travel times. Then, the average speed for each section was calculated for each ramp meter location. The average speed was also calculated over the entire corridor. The calculations were performed over the ramp meters hours of operation (6:00-9:00 AM, for the Westbound, and 3:00-7:00 PM, for the Eastbound).

Vehicle Hours Traveled (VHT)

The vehicles hours travelled (VHT) was calculated for each strategy by multiplying the throughput by the travel time. The VHT were calculated for each section and aggregated for the entire corridor. The calculations were performed over the ramp meters' hours of operation (6:00-9:00 AM, for the Westbound, and 3:00-7:00 PM, for the Eastbound).

DATA COLLECTION AND DESCRIPTION OF TRAFFIC CONDITIONS

Data Collection

In this study, the selected ramp metering strategies were tested using a simulation model for I-12 corridor. The simulation model requires geometric and traffic data to be collected to be built. The geometric data include the number of lanes along the I-12 corridor, the number of lanes on the on-ramps and the off-ramps, and the horizontal alignment of the corridor. These data were obtained using Google Maps. For the number of lanes, Geaux Wider program web page was used to account for the construction taking place on I-12 that is intended to increase the number of lanes at some sections of the corridor. For the traffic data, include speed limits, actual travel time, and traffic volumes. The speed limits information along the corridor as well as on the on-ramps and the off-ramps were obtained from the LADOTD webpage. The travel time and traffic volumes data were collected during the operation hours of the ramp meters.

For the traffic volumes, the Advanced Traffic Management Systems (ATMS) software was used to control the cameras mounted on I-12 to record videos for 20 different locations along the I-12 corridor. The video recordings covered all merging (on-ramps) and diverging (off-ramps) locations during the operation hours of the ramp meters (6:00-9:00 am for the westbound and 3:00-7:00 pm for the eastbound). Because of the limited number of available cameras, the video recordings were collected over three weekdays (Monday, Tuesday, and Wednesday). Some of the recorded videos were repeated to guarantee incident free data. Manual counts were then performed on the recorded videos which added up to 242 hours of counts. For each location, traffic volumes on the mainline as well as the ramps were counted broken down by 15 minutes. Manual vehicle classification was also performed during the counts to account for the percentage of heavy vehicles in the traffic. A sample of the counts is shown in Table 1. In order to account for that the recordings were obtained over different weekdays, the counted traffic volumes were balanced.

The travel times were obtained from the BlueTOAD data base. The collected travel time data were obtained to cover the periods of the video recordings. Some weekdays did not have enough travel time data because of the sample size issue of the Bluetooth data. This resulted in that the travel times for some hours were missing. Therefore, for these specific

hours, the travel times were obtained for the same days but in different months. A sample of the collected travel time data is shown in Table 2 and Table 3.

Table 1
Sample of traffic counts

| Duration | | Mainline | | On-Ramp | |
|----------|------|---------------------|-------------|---------------------|-------------|
| From | To | Total # of Vehicles | # of Trucks | Total # of Vehicles | # of Trucks |
| 3:00 | 3:15 | 1160 | 113 | 96 | 0 |
| 3:15 | 3:30 | 1174 | 83 | 110 | 8 |
| 3:30 | 3:45 | 1233 | 105 | 101 | 0 |
| 3:45 | 4:00 | 1253 | 30 | 97 | 14 |
| 4:00 | 4:15 | 1302 | 90 | 121 | 14 |
| 4:15 | 4:30 | 1313 | 120 | 126 | 8 |
| 4:30 | 4:45 | 1281 | 60 | 134 | 23 |
| 4:45 | 5:00 | 1014 | 83 | 126 | 0 |
| 5:00 | 5:15 | 1117 | 53 | 151 | 8 |
| 5:15 | 5:30 | 1082 | 90 | 119 | 8 |
| 5:30 | 5:45 | 1172 | 60 | 106 | 14 |
| 5:45 | 6:00 | 1065 | 30 | 93 | 0 |
| 6:00 | 6:15 | 1132 | 90 | 94 | 8 |
| 6:15 | 6:30 | 980 | 135 | 61 | 23 |
| 6:30 | 6:45 | 864 | 90 | 75 | 0 |
| 6:45 | 7:00 | 759 | 98 | 60 | 0 |

Table 2
Sample of Bluetooth data (Segment numbers and descriptions)

| | PairID | Active | OD | Distance | Direction | From | To | Pair Name |
|----|--------|--------|----|----------|-----------|------|------|---|
| 1 | 799 | Y | N | 5.7 | E | 1012 | 1023 | Essen (u1012) to Oneal (u1023) |
| 2 | 804 | Y | N | 8.91 | E | 1012 | 1014 | Essen (u1012) to Range (u1014) |
| 3 | 1665 | Y | N | 0.77 | E | 1012 | 1019 | Essen WB (u1012) to Jefferson EB (u1019) |
| 4 | 1705 | Y | N | 1.77 | E | 1012 | 1015 | Essen WB (u1012) to NB Airline EB (u1015) |
| 5 | 1701 | Y | N | 2.96 | E | 1012 | 1022 | Essen WB (u1012) to Sherwood EB (u1022) |
| 6 | 1704 | Y | N | 2.63 | E | 1012 | 1021 | Essen WB (u1012) to Sherwood WB (u1021) |
| 7 | 1664 | Y | N | 0.77 | W | 1019 | 1012 | Jefferson EB (u1019) to Essen WB (u1012) |
| 8 | 1104 | Y | N | 4.13 | E | 1019 | 1018 | Jefferson EB (u1019) to Millerville EB (u1018) |
| 9 | 1666 | Y | N | 0.99 | E | 1019 | 1015 | Jefferson EB (u1019) to NB Airline EB (u1015) |
| 10 | 1700 | Y | N | 2.19 | E | 1019 | 1022 | Jefferson EB (u1019) to Sherwood EB (u1022) |
| 11 | 1703 | Y | N | 1.86 | E | 1019 | 1021 | Jefferson EB (u1019) to Sherwood WB (u1021) |
| 12 | 802 | Y | N | 3.3 | E | 1016 | 1017 | Juban (u1016) to Walker (u1017) |
| 13 | 838 | Y | N | 5.7 | W | 1016 | 1023 | Juban to O'Neal Westbound (u1016 to u1023) |
| 14 | 3940 | Y | N | 6.73 | W | 1016 | 1018 | Juban WB (u1016) to Millerville WB (u1018) |
| 15 | 791 | Y | N | 2.3 | W | 1016 | 1014 | Juban WB (u1016) to Range WB (u1014) |
| 16 | 1678 | Y | N | 3.2 | W | 1013 | 1015 | Millerville EB (u1013) to NB Airline EB (u1015) |
| 17 | 1691 | Y | N | 0.72 | E | 1013 | 1023 | Millerville EB (u1013) to O'Neal WB (u1023) |
| 18 | 1669 | Y | N | 3.83 | E | 1013 | 1014 | Millerville EB (u1013) to Range WB (u1014) |
| 19 | 1677 | Y | N | 2.01 | W | 1013 | 1022 | Millerville EB (u1013) to Sherwood EB (u1022) |

Table 3
Sample of Bluetooth data (Travel time data)

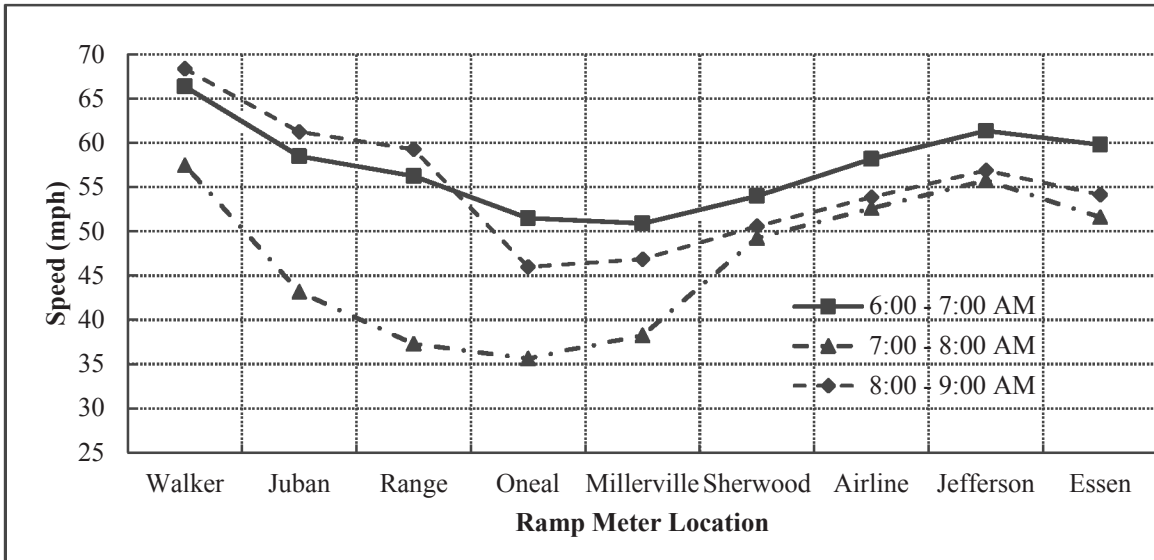
| | PairID | TravelTime | DateTime |
|----|--------|------------|---------------------|
| 1 | 1675 | 155 | 2014-11-07 10:30:00 |
| 2 | 1675 | 156 | 2014-11-07 10:45:00 |
| 3 | 1675 | 147 | 2014-11-07 11:00:00 |
| 4 | 1675 | 151 | 2014-11-07 11:15:00 |
| 5 | 1675 | 154 | 2014-11-07 11:30:00 |
| 6 | 1675 | 156 | 2014-11-07 11:45:00 |
| 7 | 1675 | 155 | 2014-11-07 12:00:00 |
| 8 | 1675 | 149 | 2014-11-07 12:15:00 |
| 9 | 1675 | 152 | 2014-11-07 12:30:00 |
| 10 | 1675 | 149 | 2014-11-07 12:45:00 |
| 11 | 1675 | 153 | 2014-11-07 13:00:00 |
| 12 | 1675 | 153 | 2014-11-07 13:15:00 |
| 13 | 1675 | 149 | 2014-11-07 13:30:00 |
| 14 | 1675 | 147 | 2014-11-07 13:45:00 |
| 15 | 1675 | 157 | 2014-11-07 14:00:00 |
| 16 | 1675 | 155 | 2014-11-07 14:15:00 |
| 17 | 1675 | 152 | 2014-11-07 14:30:00 |
| 18 | 1675 | 159 | 2014-11-07 14:45:00 |
| 19 | 1675 | 161 | 2014-11-07 15:00:00 |

Description of Traffic Conditions

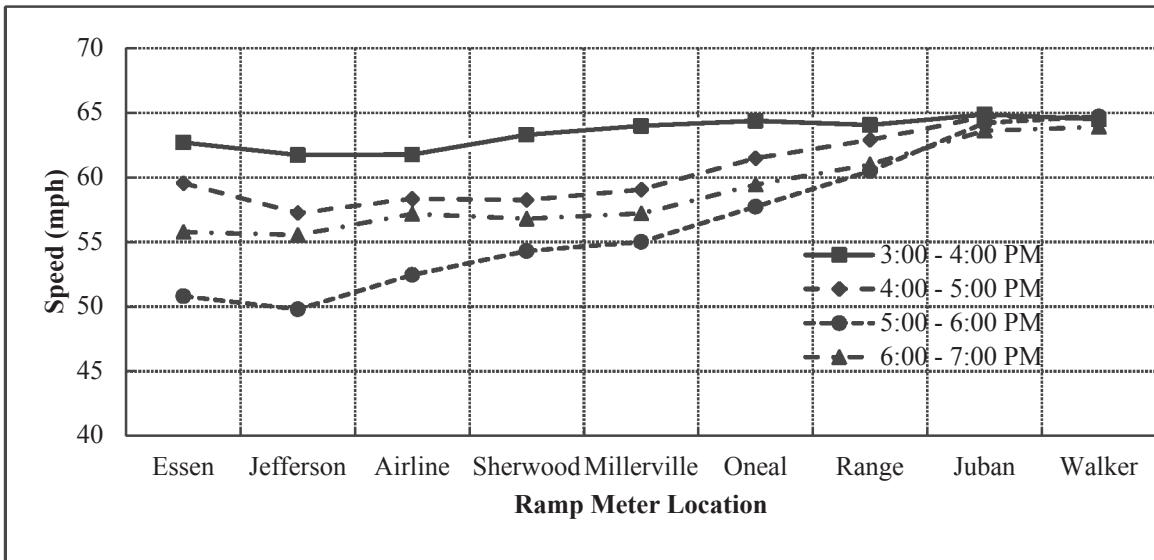
The speed profiles along the I-12 corridor were used to understand the traffic conditions at which the I-12 bounds (eastbound and westbound) are operating. The speed data at the different locations of I-12 that were calculated using the collected travel time data. The speed profiles for the eastbound and westbound directions are shown in Figure 5. For the westbound direction, the speed profiles show that at the beginning of the operating hours of the ramp meters (at 6:00 am), the speed value is higher than 55 mph at most of the ramp meters' locations. The speed drops below 55 mph at only three locations: O'neal, Millerville, and Sherwood. At 7:00 am, the speed drops to below 55 mph almost along the entire westbound direction, and it drops to as low as around 35 mph at Range, O'neal and Millerville. Then, by the end of the ramp meters' hours of operation, the speeds go up to more than 50 mph, except at O'neal and Millerville. These changes in the speed show that the westbound direction suffers from bottlenecks at different locations that cause the high drops in the travel speed. The most affected locations, according to the speed profiles, are O'neal and Millerville.

On the other hand, for the eastbound direction, the speed profiles show that with the beginning of the operating hours of the ramp meters (at 3:00 pm), the speed value higher than 60 mph along the entire corridor. The speed also goes up to as high as 65 mph at some locations including Walker and Juban. At 4:00 pm, the speed starts to drop to below 60 mph at some locations starting from Essen to Millerville. Then, at 5:00 pm, the speeds drop to its lowest values during the rush hours (3:00 to 7:00 pm), but it remains higher than 50 mph along the entire corridor. By the end of the rush hours, at 6:00 pm, the speed goes up again to above 55 mph along the entire corridor. The speed profiles over the four hours of the ramp meters operation show that the speed drops take place starting from Essen lane. Then, the speed starts to go up as the vehicles travel towards Juban and Walker, where the speeds are maintained all the time at 63 to 65 mph.

The discussion of the speed profiles shows that, unlike the westbound direction, there are no bottlenecks that can be detected on the eastbound direction, especially with the smooth speed profiles that are all the time higher than 50 mph. This shows that while the westbound suffers from bottlenecks at some locations, the traffic on the eastbound is free flowing along the entire corridor.



(a) Westbound



(b) Eastbound

Figure 5
Section-by-section average speed results (sec/veh)

I-12 SIMULATION MODEL

The microsimulation VISSIM software was chosen to test the selected ramp metering strategies on I-12. VISSIM was chosen because of its flexibility in networks' coding and simulation. In addition, the availability of 10 licenses of VISSIM software at the ITS lab, at the LTRC, helped in making the decision to choose VISSIM as the assessment tool in this study. With its Vehicle Actuated Program (VAP), VISSIM provides the capability to simulate Active Traffic Management (ATM) applications such as ramp meters. In the following sections, the I-12 model coding and calibration are discussed.

I-12 Corridor Model Encoding

The study I-12 corridor was encoded in VISSIM 6 microsimulation software. The geometric model was first built using scaled high definition up-to-date images obtained from Google Maps. The geometric data collected about the number of lanes along the corridor and on the on-ramps and off-ramps and the construction work were accounted for in the model. Speed limits were then assigned to the I-12 main stream as well as its on and off-ramps using the desired speed distributions feature in VISSIM. Using the balanced and classified traffic volumes counted from the collected video recordings, the vehicle compositions and traffic flows were defined in the I-12 simulation model.

The ramp meters and the current detectors' locations were identified using as-built-footprints provided by Stantec Consultancy Company. The required signal heads along with the detectors for queue override were placed on the on-ramps in the simulation model according to the information obtained from the footprints. Additional detectors were then placed according to the requirements of each of the tested ramp metering strategy.

The VAP interface was used to develop the required programs for the three ramp metering strategies: fixed-time, which serves as the base case, ALINEA that represents the local ramp metering strategy, and Mixed, which includes the coordinated and the local ramp metering strategies, as shown in Figure 3. The queue override strategy was also programmed using the VAP interface to work with the fixed-time strategy, to represent the current in-situ situation on I-12, and with ALINEA. For the fixed-time strategy, the queue override is activated whenever the vehicles on the ramp spill back until they reach the very end of the ramp. The queues in this case are detected using video detection by cameras mounted at the end of each ramp. This is not the case for ALINEA strategy, as the queue detection is performed differently as discussed in the research methodology.

The following task after the network is encoded and the different strategies are programmed was to calibrate the simulation model. The simulation model calibration is required to guarantee that the I-12 simulation model operates at conditions that are as close as possible to the actual conditions. Two main performance measures were used for the calibration: traffic flows and speed profiles. In order to obtain these values from the simulation model, data collection points and travel time sections were placed along the I-12 corridor model as well as at the entrances of the on-ramps and the exits of the off-ramps. The values of each measure were obtained from 20 simulation runs for the fixed-time strategy with the queue override strategy (the base case). The results were also obtained for different simulation scenarios by changing the car following and lane changing parameters of the simulation model.

Simulation Model Calibration

The simulation model calibration was performed through dealing with three main groups of parameters: the car following parameters, the lane changing parameters, and the routing decisions. Each group of parameters is discussed in the following sections.

Car Following Parameters

The car following behavior in VISSIM is simulated based on two main car following models: the Wiedemann99 and the Wiedemann74. The Wiedemann99 model accounts for modeling the car following behavior on freeways while the Wiedemann74 model accounts for the car following behavior on the urban/arterial roads. For the I-12 study corridor, the car following behavior was calibrated considering the freeway Wiedemann99 model.

The calibration was performed by changing several parameters that are shown in Figure 6. Different values were tested for three car following parameters. These parameters include the look ahead distance, CC0, CC1, and CC2. The look ahead distance parameters controls the smoothness of the merging and diverging maneuvers by providing either longer or shorter look ahead distances. Only the number of observed vehicles was changed to either 3 or 4 for some of the merging and diverging areas. The remaining parameters that control the car following behavior are called the 10 Cs; a brief description to each parameter is shown in

Table 4. Only three parameters were calibrated which include CC0, CC1, and CC2 as they have the highest influence on the lane capacity and the car following behavior. CC0 is the desired standstill gap distance between two vehicles; CC1 is the desired headway time between the two moving vehicles; and, CC2 is an additional threshold distance the following vehicle can keep with leading one in addition to the standstill distance before it starts to accelerate to decrease gap distance back to CC1. These three parameters control the desired safety distance during standstill and moving conditions and, in turn, control the lane capacity.

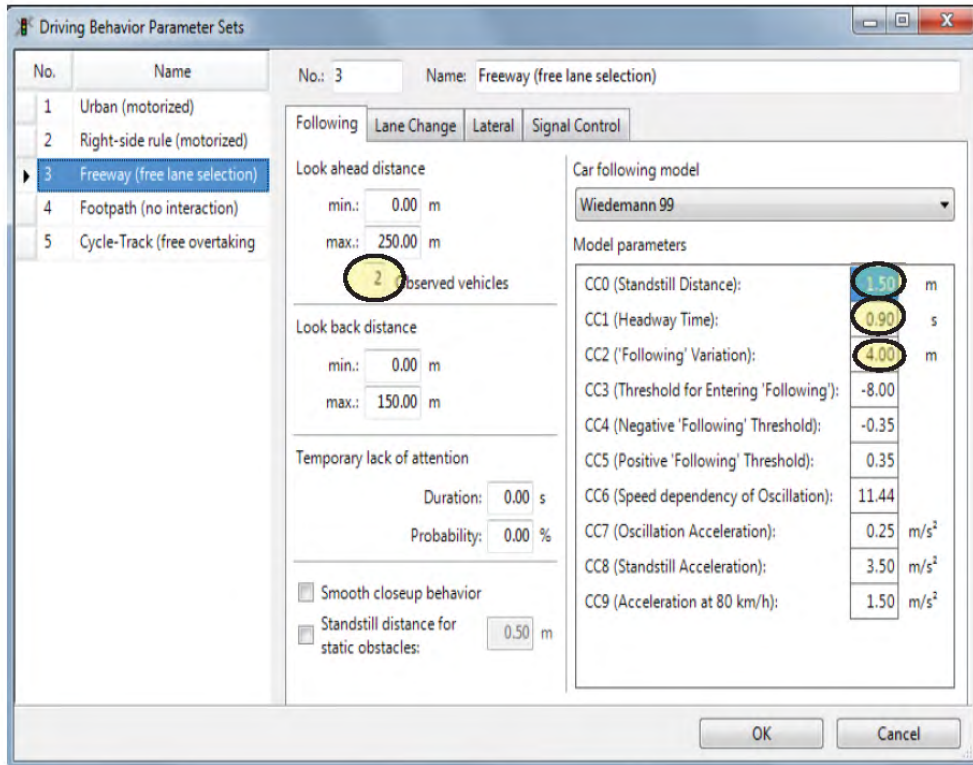


Figure 6
Parameters of Wiedemann99 car-following model in VISSIM 6

Table 4
Wiedemann99 parameters (34)

| Category | VISSIM Code | Description | Default Value |
|--------------------|--------------------|---|-------------------------|
| Thresholds for Dx | CC0 | Standstill distance: Desired distance between lead and following vehicle at v = 0 mph | 4.92 ft |
| | CC1 | Headway Time: Desired time in seconds between lead and following vehicle | 0.90 sec |
| | CC2 | Following Variation: Additional distance over safety distance that a vehicle requires | 13.12 ft |
| | CC3 | Threshold for Entering 'Following' State: Time in seconds before a vehicle starts to decelerate to reach safety distance (negative) | -8.00 sec |
| Thresholds for Dv | CC4 | Negative 'Following' Threshold: Specifies variation in speed between lead and following vehicle | 0.35 ft/s |
| | CC5 | Positive 'Following' Threshold: Specifies variation in speed between lead and following vehicle | 0.35 ft/s |
| | CC6 | Speed Dependency of Oscillation: Influence of distance on speed oscillation | 11.44 |
| Acceleration Rates | CC7 | Oscillation Acceleration: Acceleration during the oscillation process | 0.82 ft/s ² |
| | CC8 | Standstill Acceleration: Desired acceleration starting from standstill | 11.48 ft/s ² |
| | CC9 | Acceleration at 50 mph: Desired acceleration at 50 mph | 4.92 ft/s ² |

Lane Changing Parameters

The Willmann and Sparmann (1978) model is used in VISSIM to control the lane changing behavior of vehicles. The lane changing parameters that were calibrated include the deceleration rates and the cooperative lane changing; See Figure 7. These parameters determine the way vehicles interact during lane change maneuvers.

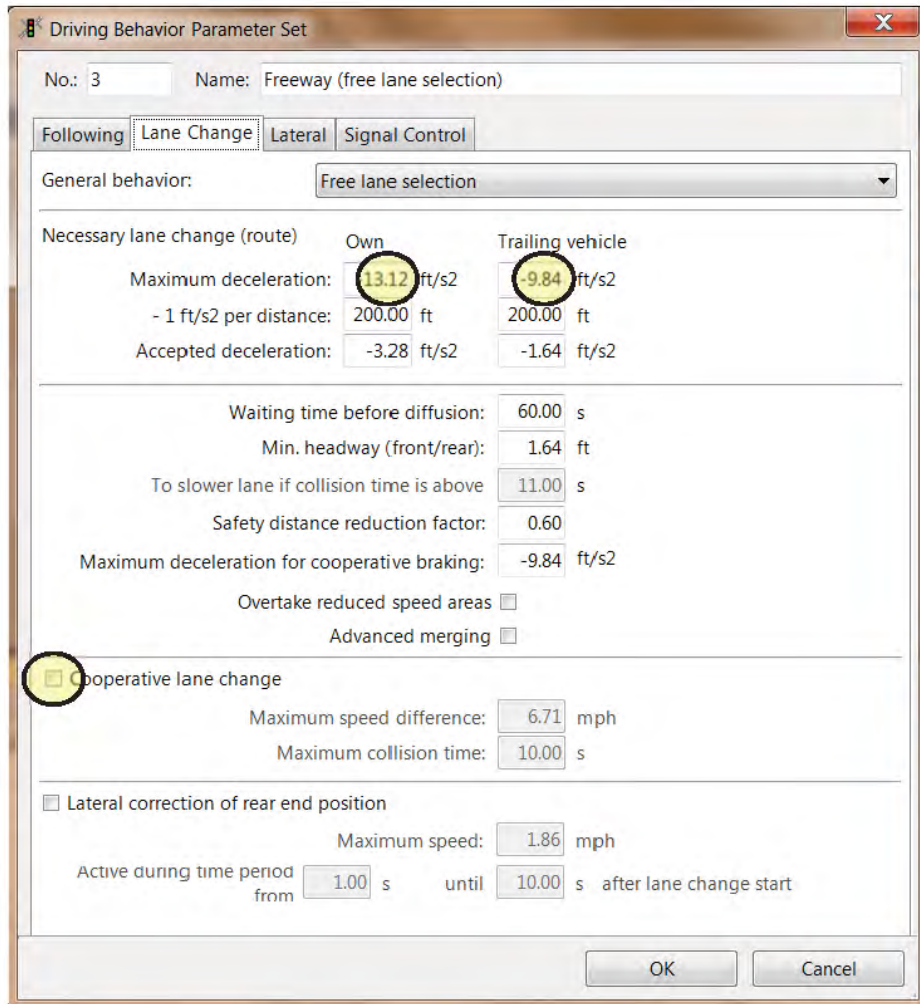


Figure 7
Parameters of Wiedemann and Reiter (1992) Lane changing model in VISSIM

Lane Changing Distance and Routing Decision Points

The lane changing distance determine where a lane changing decision at the connectors' locations is performed. The routing decision point's represent where a merging and/or a diverging decision is made in the network. Figure 8 shows the lane changing distance parameter in VISSIM. These two parameters help, in addition to the lane changing parameter, to control the smoothness of the merging and diverging maneuvers at the on-ramps and off-ramps locations, respectively.

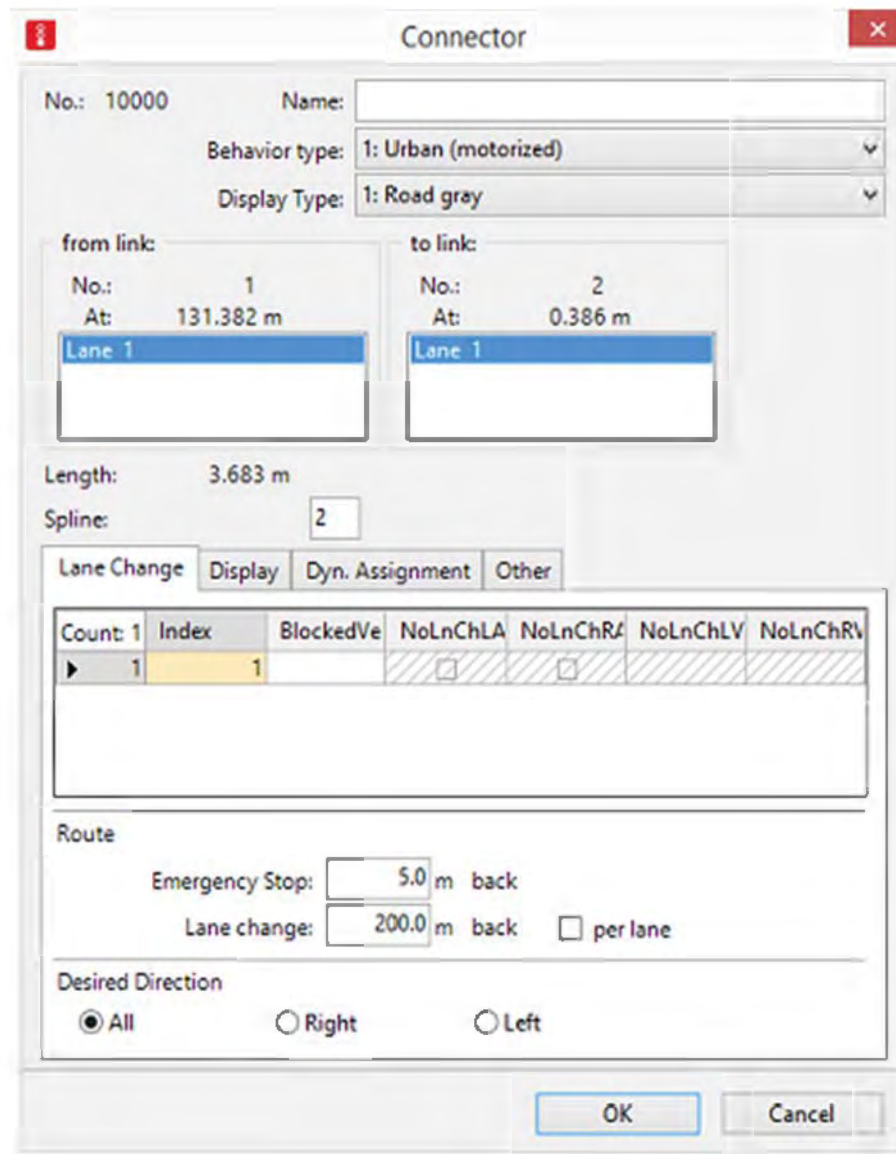


Figure 8
Parameters available for editing for each individual connector

Parameters Calibration

The different parameter were changed in several simulation runs until they are calibrated. The main objective of the calibration was to make the I-12 simulation model operating at traffic conditions that are as close as possible to the actual conditions. The calibration runs were performed considering fixed-time ramp metering strategy and the queue override strategy with the queue detectors placed at the very end of the on-ramps.

For the car following parameters, the selected four parameters were changed over different simulation trials, as shown in Table 5. These values were selected so that realistic traffic conditions can be obtained. The values were also selected based on the recommended values by Mai et al. (35).

Table 5
Driving behaviors used in this study

| Driving behavior | Observed vehicles | C0 | C1 | C2 |
|------------------|-------------------|-----|------|------|
| 1 | 2 | 4.9 | 0.9 | 13.1 |
| 2 | 3 | 4.9 | 1.1 | 13.1 |
| 3 | 4 | 6.0 | 1.2 | 13.1 |
| 4 | 4 | 4.9 | 0.9 | 13.1 |
| 5 | 4 | 5.5 | 1.5 | 20.0 |
| 6 | 2 | 5.5 | 1.3 | 20.0 |
| 7 | 3 | 5.5 | 1.5 | 20.0 |
| 8 | 4 | 4.9 | 0.85 | 6.6 |

In some simulation runs, while calibrating the car following parameters, some vehicles experienced unexpected stopping at the diverging locations, in the vicinity of the off-ramps. This was due to that those vehicles failing to perform the required lane changing maneuvers to reach the exit causing unrealistic congestion. These unexpected stops resulted in high congestions upstream the off-ramps locations. In order to overcome this problems, the lane changing parameters were calibrated. The cooperative lane changing was activated; in addition, the deceleration rates for both the lane changing vehicle and the trailing vehicle were set to 25 ft/sec². Using the cooperative lane changing property allowed the trailing vehicles to slow down in order to make wider gaps available for the vehicles performing the lane changing maneuvers. Despite the selected deceleration rate value was not conforming to the recommended values by Mai et al. (35), it was able with the help of the cooperative lane changing feature to resolve the unexpected stops issue.

Figure 9 shows the traffic volumes for the approved trial over one hour of the ramp meters' operation time (from 6:00 to 7:00 AM) for the westbound direction. Similarly, Figure 10 shows the traffic volumes for the approved calibration trial over one hour of the ramp meters' operation time (from 3:00 to 4:00 PM) for the eastbound direction. The results show that the difference between the approved trial's traffic volumes and the actual traffic volumes do not exceed 4.0% for the westbound direction and 2.0 % for the eastbound direction. In most

cases, these differences were as low as 0% along the entire corridor. Similar results were obtained for the speed profiles on the eastbound and the westbound directions. Figure 11 shows the speed profile values for the approved calibration trial over one hour of the ramp meters' operation time (from 8:00 to 9:00 AM) for the westbound direction. Similarly, Figure 12 shows the speed the profile values for the approved calibration trial over one hour of the ramp meters' operation time (from 4:00 to 5:00 AM) for the eastbound direction. The results show that while the maximum speed difference between the approved trial and actual values were 15% for the westbound direction and 14% for the eastbound direction, the average difference was as low as 3% for both directions. In summary, the calibrated results give a good indicator that the I-12 simulation model operates at traffic conditions that have a very close pattern to the in-situ conditions.

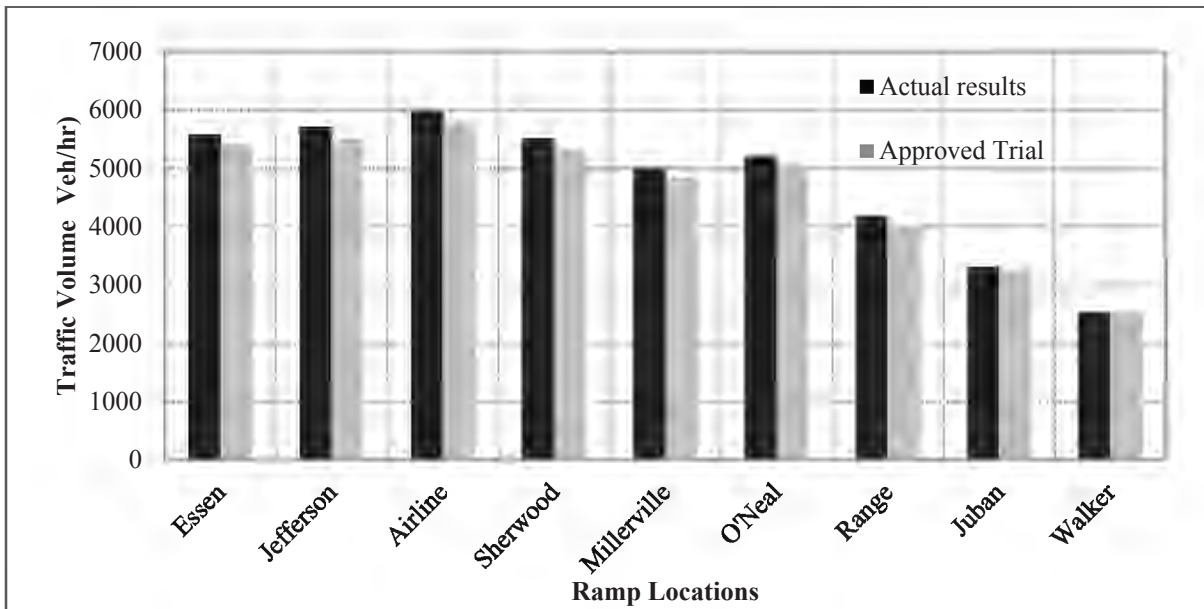


Figure 9
Final simulation model hourly volumes compared to actual ones for the westbound direction

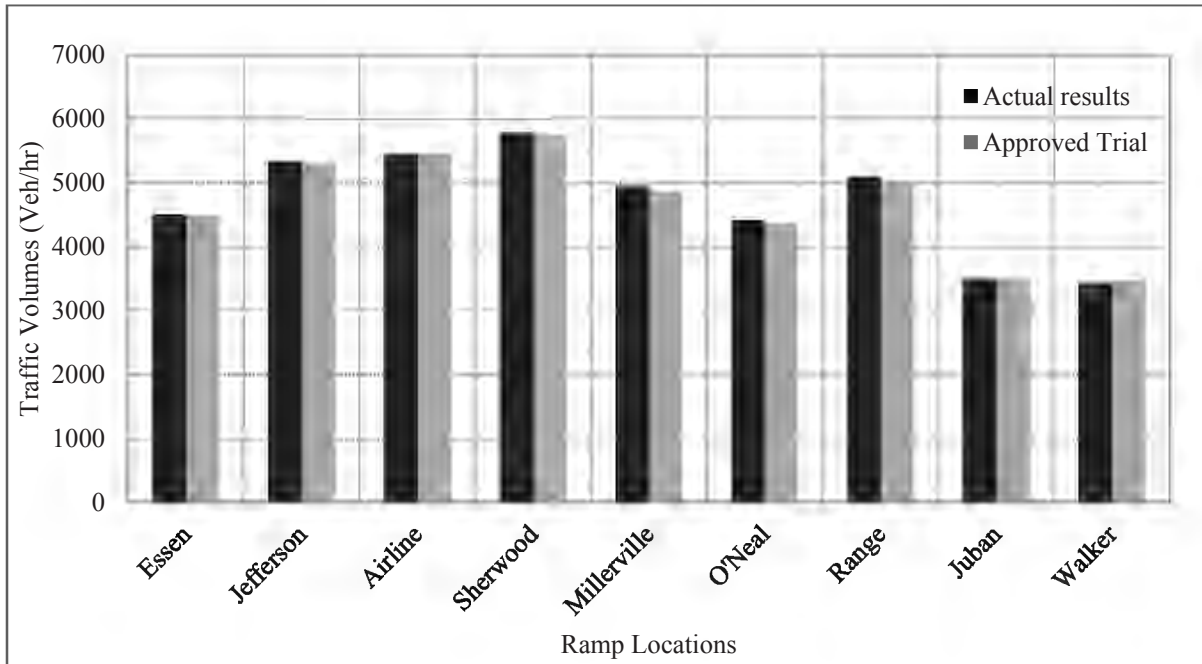


Figure 10
Final simulation model hourly volumes compared to actual ones for the eastbound direction

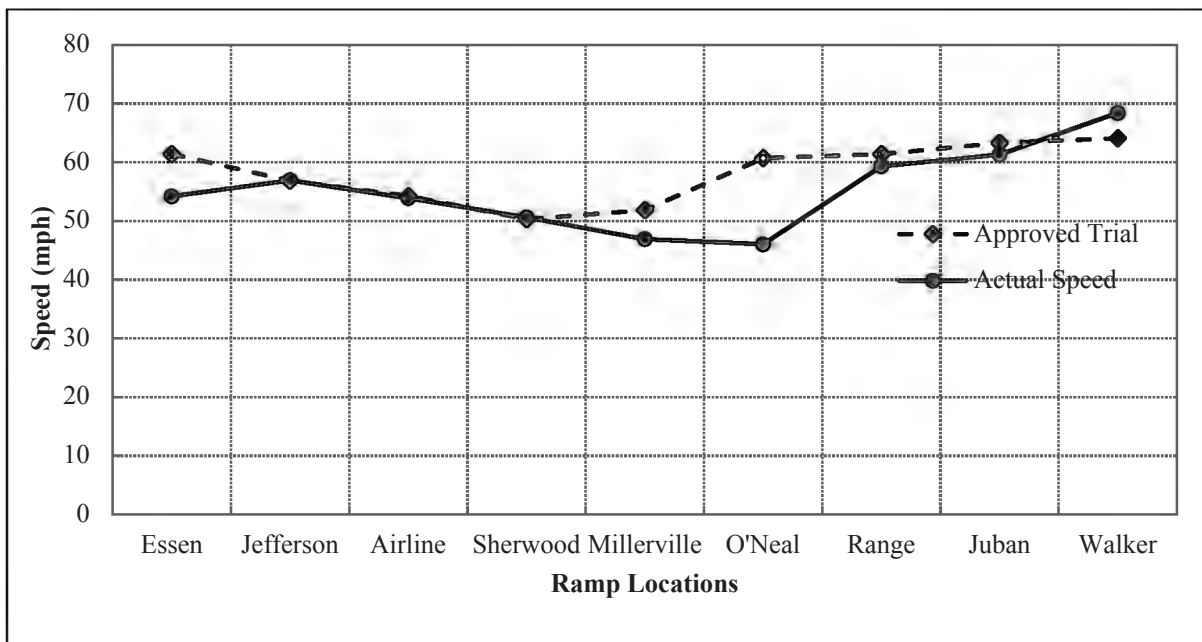


Figure 11
Actual speed profile along the I-12 along with the selected model results and other trials for the westbound direction

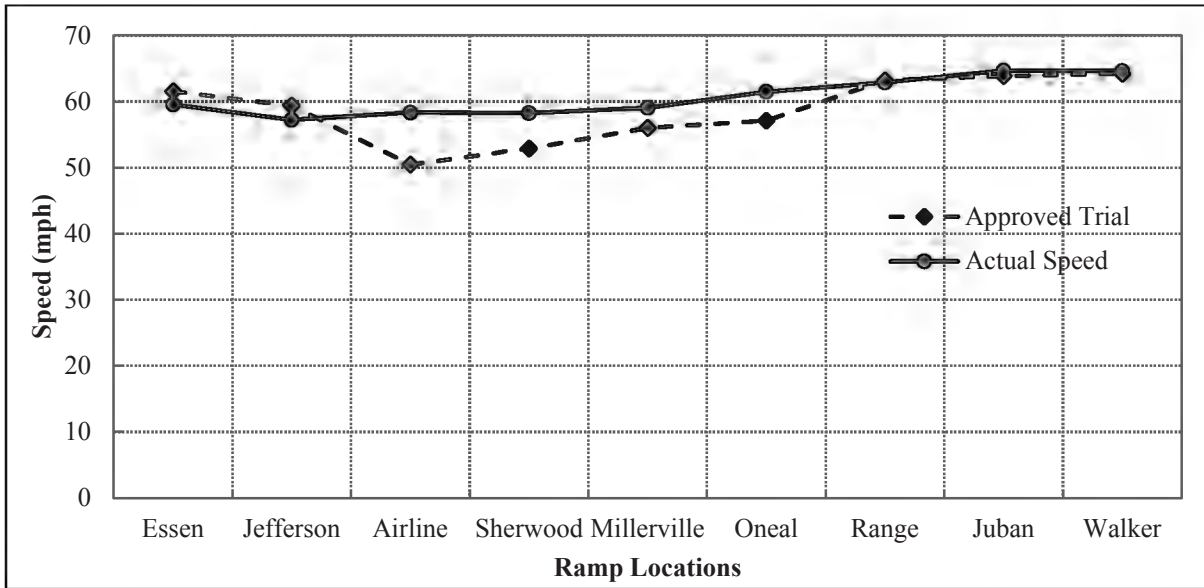


Figure 12
Actual speed profile along the I-12 along with the selected model results and other trials for the eastbound direction

Calibrating ALINEA Parameters

The ALINEA strategy operated based on three main parameters: the optimum occupancy on the mainline downstream the on-ramp, the downstream detector distance at which the optimum occupancy is required, and the gain factor (KR). While some of these parameters have recommended values in the literature, they are site-specific. Therefore, the three parameters were calibrated in order to find the optimal values that can achieve superior improvements in the traffic conditions on I-12. As such, different values were tested for each parameter. More specifically, the optimum occupancy parameter was set to 0.1, 0.2, 0.3, and 0.4; the gain factor KR was set to 60, 70, and 80 Veh/hr; and, finally, the downstream detector distance was set to 200, 500 and 1000 feet downstream the on-ramp.

Using the selected values for the different parameters, 20 simulation runs were performed using the calibrated I-12 simulation model on each of 36 combinations for ALINEA. For each simulation run, the three performance measures (the speed, travel time, and VHT) were obtained. The results were obtained throughout the ramp meters hours of operation, 6:00 to 9:00 AM for the westbound and 3:00 to 7:00 PM for the eastbound.

The results of the 36 combinations were comparatively evaluated using Multivariate Analysis of Variance (MANOVA) test. MANOVA analysis was performed with the speed, travel time, and VHT treated as the dependent variables and the three ALINEA parameters treated as the independent variables. Then, for the ALINEA parameters that were significantly affecting the performance measures, Post Hoc test (Tukey) was conducted to identify the optimal combination of parameters. Both the MANOVA and the Post Hoc analysis were performed at 95% level of confidence, see Appendix B.

The results indicated that, for the eastbound direction, the gain factor and the optimum occupancy had no significant effect on the dependent variables. Although, the detector's distance had the highest impact on the dependent variables, its effect was statistically not significant. Therefore, for the eastbound, the optimal values of ALINEA were selected based on the field conditions. The simulation results showed that the downstream actual occupancy was in the range of 0.3 to 0.4 most of the time. More so, the simulation model showed that these values take place within distance of 500 to 1000 ft downstream the on-ramps. As such, in order to detect and improve the traffic conditions on the mainline, a detector distance of 1000 ft with an optimum occupancy value of 0.2 were selected. For the gain factor, the recommended value in the literature, 70 veh/hr, was used.

Similarly, for the westbound direction, the gain factor and the optimum occupancy had no significant effect on the dependent variables. However, the detector's distance was affecting the performance measures significantly. As such, further Post Hoc tests were performed to identify the optimal value. The results indicated that detector's distance value of 500 ft achieved the most significant improvements in the speed, travel time, and VHT values. For the optimum occupancy, similar to the eastbound direction and for the same reason, a value of 0.2 was selected. For the gain factor, the recommended value in the literature, 70 veh/hr, was used.

DISCUSSION OF RESULTS

Travel Time

Using the simulation results, the average travel times were calculated over the entire I-12 corridor for the eastbound and westbound directions. The travel times for the different tested strategies were calculated as average values calculated for each section in the corridor (each section is defined by a ramp meter location). In addition, the average travel times were also aggregated over the entire corridor. The calculations were performed over the ramp meters' period of operation (6:00-9:00 AM, for the westbound, and 3:00-7:00 PM, for the eastbound). In the following sections, a discussion for the corridor level travel times and the section-by-section level travel times is presented.

Corridor Level Analysis

The resulting average travel times for a vehicle to travel over the entire corridor are shown in Table 6 for the different ramp metering strategies. For the eastbound, the table shows that the travel time for the mixed ramp metering control is less than that for the fixed-time control by around 6 seconds. The table shows also that the travel time for the ALINEA is less than that of the fixed-time control by around 2 seconds. These results do not show a practical significance in the travel time improvement for the eastbound direction. On the other hand, for the westbound direction, the ALINEA local ramp metering strategy reduced the travel time by around 20 seconds when compared to the current fixed-time control. Whereas, for the mixed control the travel time was reduced by around 40 seconds which is practically more significant than the ALINEA local control case. The table shows also that the travel times for the eastbound direction are less than those for the westbound direction. The reason for that is that the eastbound is already free flowing which explains why there was no significant practical improvement in the travel times for the eastbound direction.

Table 6
Average travel time results over the corridor

| Strategy | Travel Time (sec/veh) | |
|------------|-----------------------|-----------|
| | Eastbound | Westbound |
| Mixed | 986 | 1166 |
| ALINEA | 990 | 1187 |
| Fixed-time | 992 | 1206 |

Further comparative statistical ANalysis Of VAriances (ANOVA) was performed between the different ramp metering strategies using both the sectional travel time information and the aggregated corridor travel time information. The analysis was performed at 5% level of significance to investigate the statistical significance of the travel time reductions caused by each strategy. The ANOVA test results for the corridor level are shown in Table 7. The results show that there was no significant change in the travel time between the different strategies for the eastbound direction with a p-value of 0.432. This was expected as this direction is already free flowing as shown in the speed profiles for the current traffic conditions in Figure 12. Whereas, for the westbound direction, the table shows that the travel time differences were statistically significant for both the ALINEA and the mixed strategies with a p-value of 0.001.

Table 7
Comparative ANOVA test results for the different ramp metering strategies

| Direction | Level of analysis | Sum of Squares | df | Mean Square | F | P-value |
|-----------|--------------------|----------------|----|-------------|-------|---------|
| Eastbound | Between Strategies | 420.889 | 2 | 210.445 | .852 | .432 |
| | Within Strategies | 14070.800 | 57 | 246.856 | | |
| | Total | 14491.689 | 59 | | | |
| Westbound | Between Strategies | 15865.782 | 2 | 7932.891 | 8.378 | .001 |
| | Within Strategies | 53972.516 | 57 | 946.886 | | |
| | Total | 69838.297 | 59 | | | |

For the eastbound direction, no further analysis is required because there were no statistically significant differences found in the travel time values. Whereas, for the westbound direction, to determine the strategy with the lowest travel times, Post Hoc tests (Tukey) were performed. The results in Table 8 show that no significant change in the travel time values can be found between the fixed-time and the ALINEA ramp metering strategies. Same results were found between the ALINEA and the mixed ramp metering strategies. When comparing the mixed to the fixed-time strategies, the results showed that the travel times for the mixed ramp metering strategy were significantly less than those for the fixed-time strategy.

Table 8
Post hoc Tukey test results for the different ramp metering strategies

| Direction | (I) Strategy | (J) Strategy | Mean Difference (I-J) | Std. Error | P-value | 95% Confidence Interval | |
|-----------|---------------|---------------|-----------------------|------------|---------|-------------------------|-------------|
| | | | | | | Lower Bound | Upper Bound |
| Westbound | Fixed Control | ALINEA | 19.00000 | 9.73081 | .134 | -4.4164 | 42.4164 |
| | | Mixed | 39.81804 | 9.73081 | .000 | 16.4016 | 63.2344 |
| | ALINEA | Fixed Control | -19.00000 | 9.73081 | .134 | -42.4164 | 4.4164 |
| | | Mixed | 20.81804 | 9.73081 | .091 | -2.5984 | 44.2344 |
| | Mixed | Fixed Control | -39.81804 | 9.73081 | .000 | -63.2344 | -16.4016 |
| | | ALINEA | -20.81804 | 9.73081 | .091 | -44.2344 | 2.5984 |

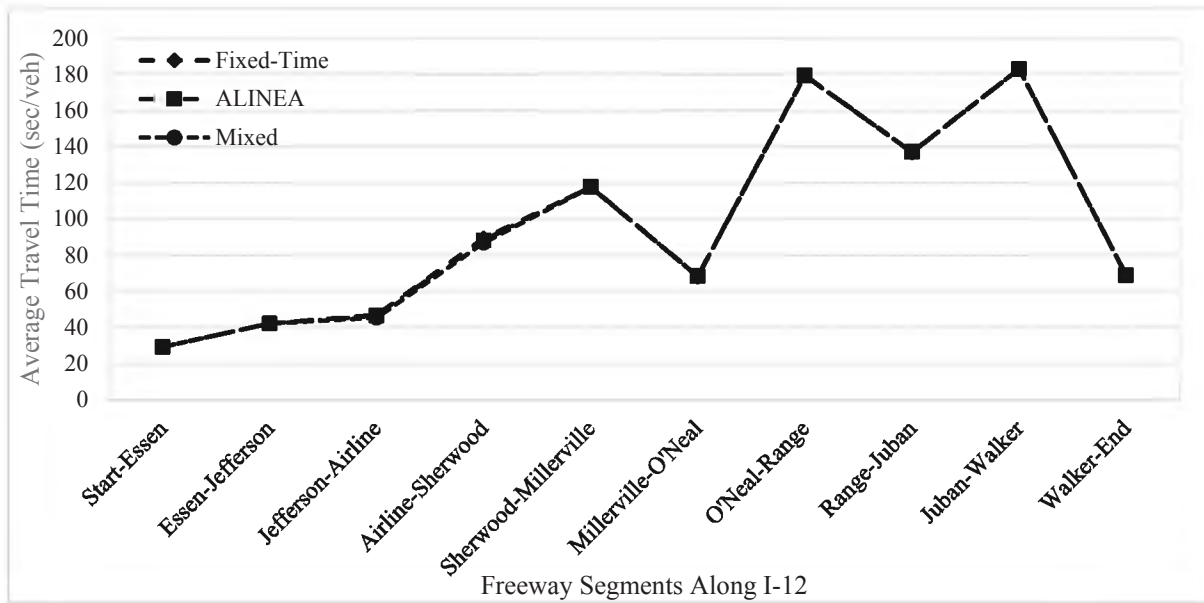
* indicates that the difference is statistically significant.

Section Level Analysis

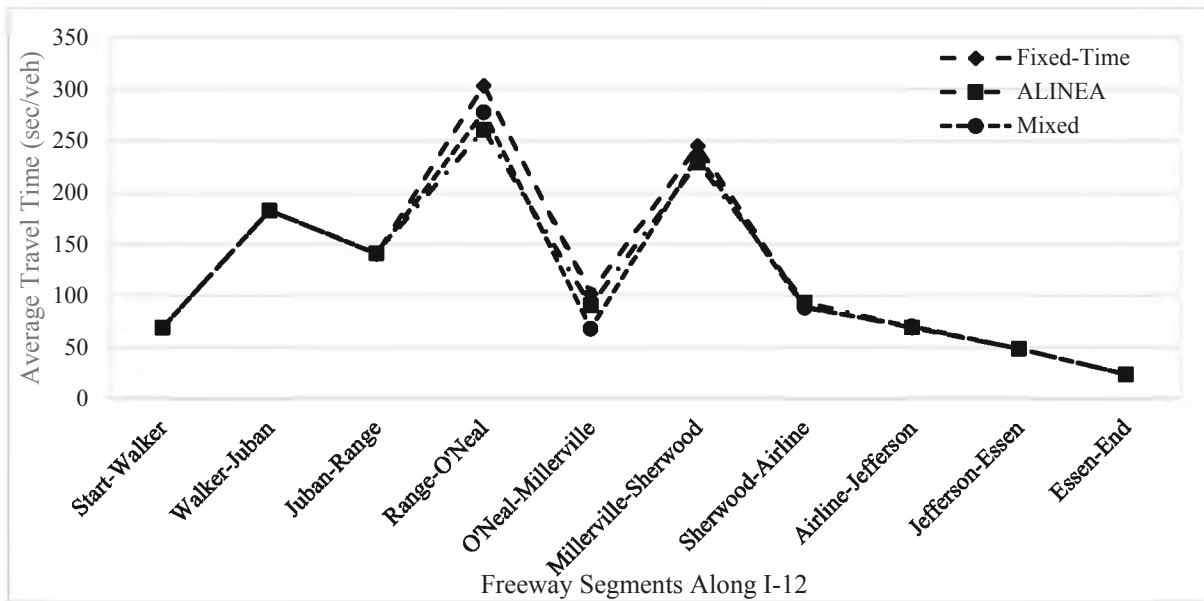
The section level analysis was performed to show more detailed section-by-section results for the impact of the different strategies, see Appendix B. The section-by-section travel times show the ramp meter locations that benefited the most from each ramp metering strategy for each direction. The travel time values for each section is shown in Figure 13. The figure shows that, for the eastbound direction, both the mixed and the ALINEA ramp metering strategies did not show any improvement in the travel time values that can be noticed at any of the ramp meter locations; see Figure 13-a. On the other hand, for the westbound direction, only three sections showed significant improvement in the travel time values when implementing the mixed and the ALINEA ramp metering strategies. As shown in Figure 13-b, these sections include the ramp meters that control the traffic between Range to O’neal, O’neal to Millerville, and Millerville to Sherwood.

The travel time improvements shown in Figure 13-b were further investigated statistically using Post Hoc pairwise Tukey test. The statistical analysis results are shown in Table 9. The table shows that, for the section between Range and O’neal, while there was no significant change in the travel time between the mixed and the ALINEA strategies, both of these strategies showed significant improvement in the travel times when compared to the fixed-time control. For the section between O’neal and Millerville, the ALINEA ramp metering strategy did not show significant improvement in the travel time; whereas, the mixed control significantly reduced the travel time values when compared to the fixed-time

control. For the section between Millerville and Sherwood, despite the mean travel times for the ALINEA and the mixed control strategies were less than that for the fixed-time control, the differences in the travel times were not statistically significant.



(a) Eastbound Direction



(b) Westbound Direction

Figure 13
Section-by-section average travel time results (sec/veh)

Table 9
Section-by-section Post Hoc Tukey test results for the different ramp metering strategies

| Dependent Variable | (I) Strategy | (J) Strategy | Mean Difference (I-J) | Std. Error | Sig. | 95% Confidence Interval | |
|----------------------|---------------|---------------|-----------------------|------------|------|-------------------------|-------------|
| | | | | | | Lower Bound | Upper Bound |
| Range-O'neal | Fixed Control | ALINEA | 42.62919 | 8.62576 | .000 | 21.8720 | 63.3864 |
| | | Mixed | 25.73510 | 8.62576 | .011 | 4.9779 | 46.4923 |
| | ALINEA | Fixed Control | -42.62919 | 8.62576 | .000 | -63.3864 | -21.8720 |
| | | Mixed | -16.89409 | 8.62576 | .132 | -37.6513 | 3.8631 |
| | Mixed | Fixed Control | -25.73510 | 8.62576 | .011 | -46.4923 | -4.9779 |
| | | ALINEA | 16.89409 | 8.62576 | .132 | -3.8631 | 37.6513 |
| O'neal-Millerville | Fixed Control | ALINEA | 11.27422 | 8.33900 | .373 | -8.7929 | 31.3413 |
| | | Mixed | 33.72709 | 8.33900 | .000 | 13.6600 | 53.7942 |
| | ALINEA | Fixed Control | -11.27422 | 8.33900 | .373 | -31.3413 | 8.7929 |
| | | Mixed | 22.45286 | 8.33900 | .025 | 2.3857 | 42.5200 |
| | Mixed | Fixed Control | -33.72709 | 8.33900 | .000 | -53.7942 | -13.6600 |
| | | ALINEA | -22.45286 | 8.33900 | .025 | -42.5200 | -2.3857 |
| Millerville-Sherwood | Fixed Control | ALINEA | 16.47363 | 7.41610 | .076 | -1.3726 | 34.3199 |
| | | Mixed | 9.91505 | 7.41610 | .381 | -7.9312 | 27.7613 |
| | ALINEA | Fixed Control | -16.47363 | 7.41610 | .076 | -34.3199 | 1.3726 |
| | | Mixed | -6.55858 | 7.41610 | .652 | -24.4048 | 11.2877 |
| | Mixed | Fixed Control | -9.91505 | 7.41610 | .381 | -27.7613 | 7.9312 |
| | | ALINEA | 6.55858 | 7.41610 | .652 | -11.2877 | 24.4048 |

Speed

Similarly, the travel speeds were calculated and averaged over the entire I-12 corridor for the eastbound and westbound directions using the simulation results. The operational speed for

the different ramp metering strategies were calculated for each ramp meter location along the corridor. The speed was also calculated using aggregated data for the entire corridor. The speed values were calculated over the ramp meters' operation periods (6:00-9:00 AM, for the westbound, and 3:00-7:00 PM, for the eastbound). In the following sections, a discussion for the corridor level speeds and the section-by-section speeds is presented.

Corridor Level Analysis

The estimated average travel speeds over the entire corridor are shown in Table 10 for the different ramp metering strategies. For the eastbound direction, the results show that the average operating speed remains almost the same at 59 mph under the three tested strategies. These results do not show any improvement for the corridor operating speed regardless the type of ramp metering strategies. While for the westbound direction, the ALINEA strategy shows a slight increase of speed from 48.7 mph for the fixed-time strategy to 49.5 mph. For the mixed control strategy, the operating speed increased to around 50.4 mph. The table also shows that the resulting speeds for the eastbound direction are more than those of the westbound direction, which is related to the fact that the eastbound direction is operating at free flow conditions.

Table 10
Average speed results over the corridor

| Strategy | Speed (mph) | |
|------------|-------------|-----------|
| | Eastbound | Westbound |
| Fixed-time | 59.0 | 48.7 |
| ALINEA | 59.2 | 49.5 |
| Mixed | 59.4 | 50.4 |

Further comparative statistical ANalysis Of VAriances (ANOVA) was performed between the different ramp metering strategies using both the sectional speed information and the aggregated corridor speed information. The analysis was performed at 5% level of significance to investigate the statistical significance of the travel time reductions caused by each strategy. The ANOVA test results for the corridor level are shown in Table 11. The results show that there was no significant change in the operating speed between the different strategies for the eastbound direction with a p-value of 0.401. Whereas, for the westbound direction, the table shows that the differences in the operating speed were statistically significant for both the ALINEA and the mixed strategies with a p-value of 0.001.

Table 11
Comparative ANOVA test results for the different ramp metering strategies (speed)

| Direction | Level of analysis | Sum of Squares | df | Mean Square | F | P-value |
|-----------|--------------------|----------------|----|-------------|-------|---------|
| Eastbound | Between Strategies | 1.493 | 2 | .746 | .929 | .401 |
| | Within Strategies | 45.782 | 57 | .803 | | |
| | Total | 47.275 | 59 | | | |
| Westbound | Between Strategies | 26.917 | 2 | 13.458 | 7.707 | .001 |
| | Within Strategies | 99.536 | 57 | 1.746 | | |
| | Total | 126.453 | 59 | | | |

For the eastbound direction, no further analysis is required because there were no statistically significant differences found in the speed values. Whereas, for the westbound direction, to determine the strategy with the highest improvement in the operating speeds, Post Hoc tests (Tukey) was performed. The results in Table 12 shows that there was no significant change in the operating speed values between the fixed-time and the ALINEA ramp metering strategies. Same results were found between the ALINEA and the mixed ramp metering strategies. However, when comparing the mixed to the fixed-time strategy, the results showed that the mixed ramp metering strategy significantly improved the operating speed with a p value of 0.001.

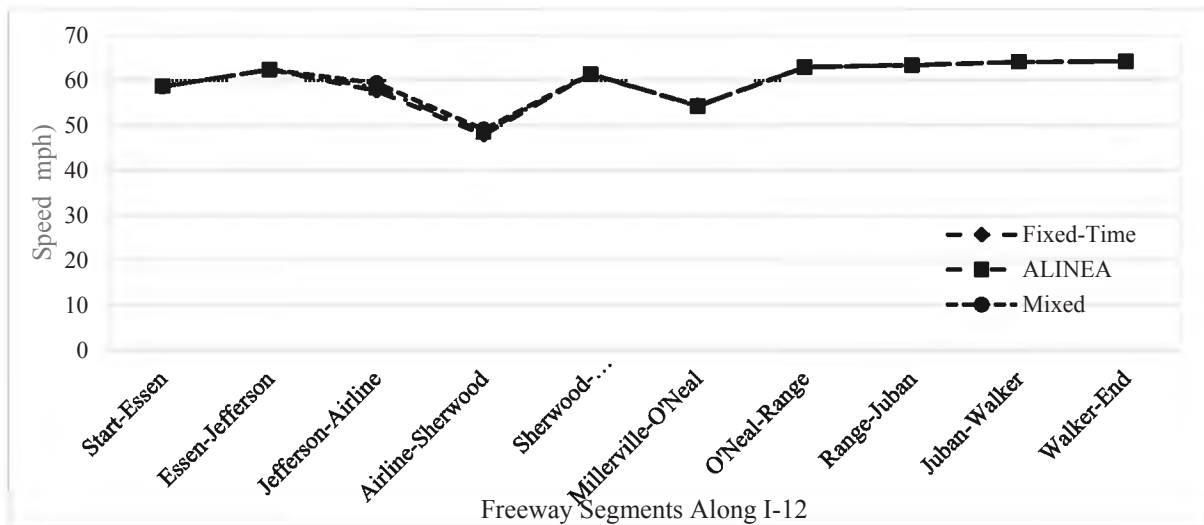
Table 12
Post Hoc Tukey test results for the different ramp metering strategies (speed)

| Direction | (I) Strategy | (J) Strategy | Mean Difference (I-J) | Std. Error | P-value | 95% Confidence Interval | |
|-----------|---------------|---------------|-----------------------|------------|---------|-------------------------|-------------|
| | | | | | | Lower Bound | Upper Bound |
| Westbound | Fixed Control | ALINEA | -.71591 | .41788 | .209 | -1.7215 | .2897 |
| | | Mixed | -1.63637* | .41788 | .001 | -2.6420 | -.6308 |
| | ALINEA | Fixed Control | .71591 | .41788 | .209 | -.2897 | 1.7215 |
| | | Mixed | -.92046 | .41788 | .079 | -1.9261 | .0851 |
| | Mixed | Fixed Control | 1.63637 | .41788 | .001 | .6308 | 2.6420 |
| | | ALINEA | .92046 | .41788 | .079 | -.0851 | 1.9261 |

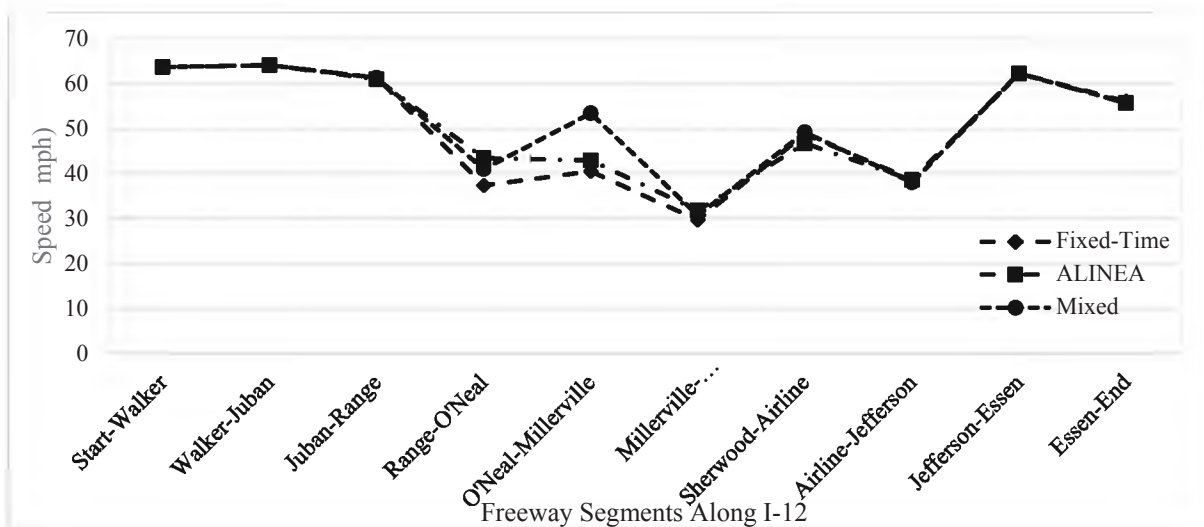
Section Level Speeds

The section level analysis was performed to show more detailed section-by-section results for the impact of the different strategies, see Appendix B. The section-by-section speed values show the ramp meter locations that benefited the most from each ramp metering strategy for each direction. The speed values for each section are shown in Figure 14. The figure shows that, for the eastbound direction, both the mixed and the ALINEA ramp metering strategies

did not show any improvement in the speed values that can be noticed at any of the ramp meter locations; see Figure 14-a. On the other hand, for the westbound direction, only two sections showed significant improvement in the operating speed values when implementing the mixed and the ALINEA ramp metering strategies. As shown in Figure 14-b, these sections include the ramp meters that control the traffic between Range to O’neal and O’neal to Millerville.



(a) Eastbound Direction



(b) Westbound Direction

Figure 14
Section-by-section average speed results (sec/veh)

The improvements in the operating speed shown in Figure 14-b were further investigated statistically using Post Hoc pairwise Tukey test. The statistical analysis results are shown in Table 13. The table shows that, for the section between Range and O’neal, while there was no significant change in speeds between the mixed and the ALINEA strategies, both of these strategies showed significant improvement in the speed when compared to the fixed-time control. For the section between O’neal and Millerville, only the fixed control strategy showed a significant increase in the speed values when compared to the fixed-time and ALINEA control strategies.

Table 13
Section-by-section Post Hoc Tukey test results for the different ramp metering strategies

| Dependent Variable | (I) Strategy | (J) Strategy | Mean Difference (I-J) | Std. Error | Sig. | 95% Confidence Interval | |
|--------------------|---------------|---------------|-----------------------|------------|------|-------------------------|-------------|
| | | | | | | Lower Bound | Upper Bound |
| Range-O’neal | Fixed Control | ALINEA | -6.10826* | 1.18055 | .000 | -8.9492 | -3.2674 |
| | | Mixed | -3.64080* | 1.18055 | .009 | -6.4817 | -.7999 |
| | ALINEA | Fixed Control | 6.10826 | 1.18055 | .000 | 3.2674 | 8.9492 |
| | | Mixed | 2.46746 | 1.18055 | .101 | -.3734 | 5.3084 |
| | Mixed | Fixed Control | 3.64080 | 1.18055 | .009 | .7999 | 6.4817 |
| | | ALINEA | -2.46746 | 1.18055 | .101 | -5.3084 | .3734 |
| O’neal-Millerville | Fixed Control | ALINEA | -2.45523 | 3.20083 | .725 | -10.1578 | 5.2473 |
| | | Mixed | -12.93043* | 3.20083 | .000 | -20.6330 | -5.2279 |
| | ALINEA | Fixed Control | 2.45523 | 3.20083 | .725 | -5.2473 | 10.1578 |
| | | Mixed | -10.47520* | 3.20083 | .005 | -18.1777 | -2.7727 |
| | Mixed | Fixed Control | 12.93043* | 3.20083 | .000 | 5.2279 | 20.6330 |
| | | ALINEA | 10.47520* | 3.20083 | .005 | 2.7727 | 18.1777 |

Vehicles’ Hours Traveled (VHT)

Using the simulation results, vehicles’ hours travelled (VHT) were calculated as the multiplication of the throughput by the average travel times. The VHT for the different strategies were calculated as average values for each section along the corridor. In addition, the VHT were also aggregated over the entire corridor. The calculations were performed over the ramp meters’ period of operation (6:00-9:00 AM, for the westbound, and 3:00-7:00 PM, for the eastbound). In the following sections, a discussion for the corridor level VHT and the section-by-section level VHT is presented.

Corridor Level Analysis

The estimated average VHT over the entire corridor are shown in Table 14 for the different ramp metering strategies. For the eastbound direction, the results show that the average VHT for the mixed ramp metering control is less than that for the fixed-time control by around 6.5 hours. The table also shows that the VHT for the ALINEA is less than that of the fixed-time control by around 2.5 hours. These results do not show any practical significance in the VHT improvement for the eastbound direction. On the other hand, for the westbound direction, the ALINEA local ramp metering strategy reduced the VHT by approximately 197 hours when compared to the current fixed-time control. Whereas, for the mixed control the VHT was reduced by around 195 hours compared to the fixed-time control which is practically has the same effect as ALINEA local control case. The table shows also that the VHT for the eastbound direction are less than those for the westbound direction, which confirms that the eastbound direction is free flowing. This explains the reason for not having significant differences in the VHT for that direction.

Table 14
Average vehicles hours travelled over the corridor

| Strategy | VHT (veh-hr) | |
|------------|--------------|-----------|
| | Eastbound | Westbound |
| Fixed-time | 992.3 | 3199.3 |
| ALINEA | 989.9 | 3002.1 |
| Mixed | 985.8 | 3004.6 |

Further comparative statistical ANalysis Of VAriances (ANOVA) was performed between the different ramp metering strategies using both the sectional VHT and the aggregated corridor VHT. The analysis was performed at 5% level of significance to investigate the statistical significance of the VHT reductions resulting from each strategy. The ANOVA test results for the corridor level are shown in Table 12. The results show that there was no significant change in the VHT between the different strategies for the eastbound direction with a p-value of 0.478. Whereas, for the westbound direction, the table shows that the VHT were significantly changing between the different strategies with a p-value less than 0.05.

Table 15
Comparative ANOVA test results for the different ramp metering strategies(VHT)

| Direction | Level of analysis | Sum of Squares | df | Mean Square | F | P-value |
|-----------|--------------------|----------------|----|-------------|--------|---------|
| Eastbound | Between Strategies | 3200.912 | 2 | 1600.456 | .748 | .478 |
| | Within Strategies | 121890.977 | 57 | 2138.438 | | |
| | Total | 125091.889 | 59 | | | |
| Westbound | Between Strategies | 512069.183 | 2 | 256034.592 | 12.956 | .000 |
| | Within Strategies | 1126430.723 | 57 | 19761.943 | | |
| | Total | 1638499.907 | 59 | | | |

For the eastbound direction, no further analysis is required because there were no statistically significant differences found in the VHT values. Whereas, for the westbound direction, to determine the strategy with the lowest VHT, Post Hoc tests (Tukey) were performed. The results in Table 16 show that no significant change in the VHT values can be found between the fixed-time and the ALINEA ramp metering strategies. Same results were found between the ALINEA and the mixed ramp metering strategies. When comparing the mixed to the fixed-time strategies, the results showed that the VHT for the mixed ramp metering strategy were significantly less than those for the fixed-time strategy.

Table 16
Post Hoc Tukey test results for the different ramp metering strategies (VHT)

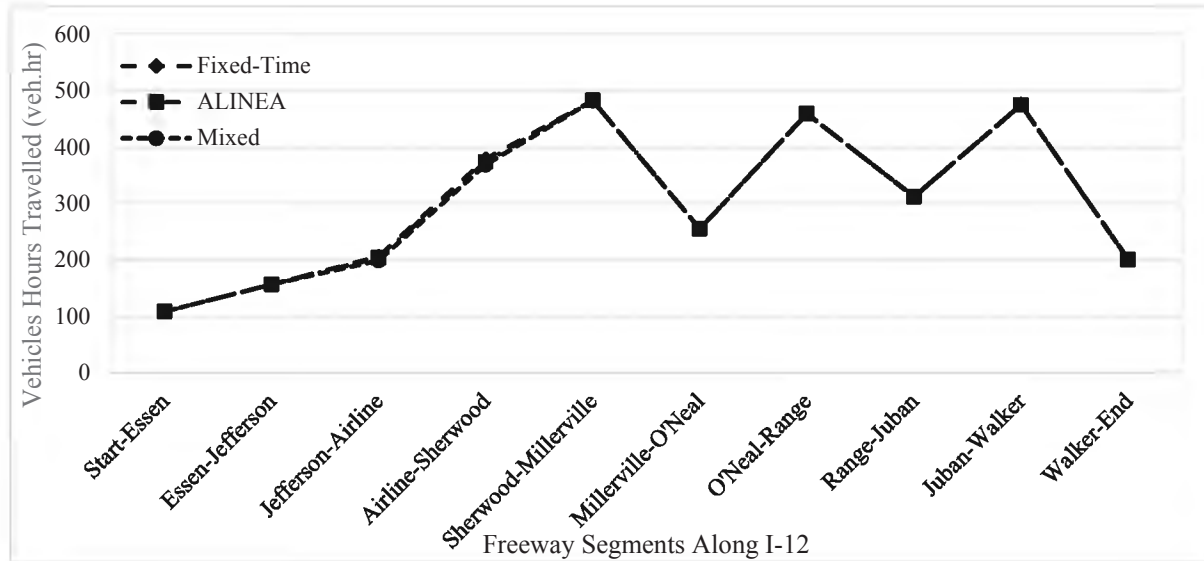
| Direction | (I) Strategy | (J) Strategy | Mean Difference (I-J) | Std. Error | P-value | 95% Confidence Interval | |
|-----------|---------------|---------------|-----------------------|------------|---------|-------------------------|-------------|
| | | | | | | Lower Bound | Upper Bound |
| Westbound | Fixed Control | ALINEA | 19.00000 | 9.73081 | .134 | -4.4164 | 42.4164 |
| | | Mixed | 39.81804* | 9.73081 | .000 | 16.4016 | 63.2344 |
| | ALINEA | Fixed Control | -19.00000 | 9.73081 | .134 | -42.4164 | 4.4164 |
| | | Mixed | 20.81804 | 9.73081 | .091 | -2.5984 | 44.2344 |
| | Mixed | Fixed Control | -39.81804* | 9.73081 | .000 | -63.2344 | -16.4016 |
| | | ALINEA | -20.81804 | 9.73081 | .091 | -44.2344 | 2.5984 |

* indicates that the difference is statistically significant.

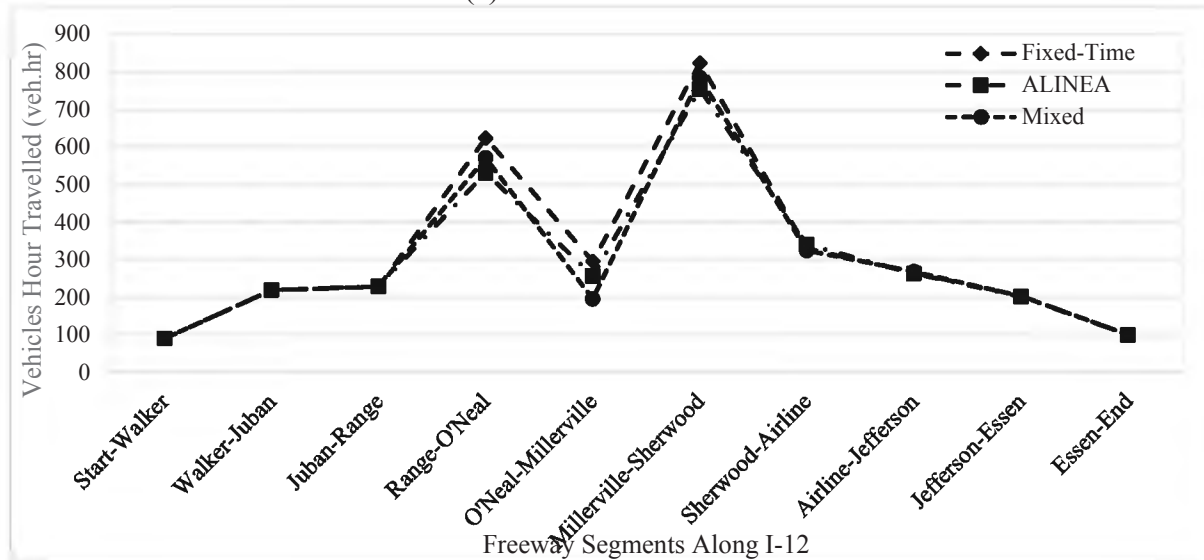
Section Level Vehicles Hours Traveled (VHT)

The section level analysis was performed to show more detailed section-by-section results for the impact of the different strategies, see Appendix B. The section-by-section VHT show the sections that benefited the most from each ramp metering strategy for each direction. The VHT values for each section are shown in Figure 15. The figure shows that, for the

eastbound direction, both the mixed and the ALINEA ramp metering strategies did not show any improvement in the VHT values that can be noticed at any of the sections; see Figure 15-a. On the other hand, for the westbound direction, only three sections showed significant improvement in the VHT values when implementing the mixed and the ALINEA ramp metering strategies. As shown in Figure 15-b, these sections include the ramp meters that control the traffic between Range to O’neal, O’neal to Millerville, and Millerville to Sherwood.



(a) Eastbound Direction



(b) Westbound Direction

Figure 15
Section-by-section average VHT results (veh.hr)

The improvements in the VHT values shown in Figure 15-b were further investigated statistically using Post Hoc pairwise Tukey test. The statistical analysis results are shown in Table 17. The table shows that, for the section between Range and O’neal, while there was no significant change in the VHT between the mixed and the ALINEA strategies, both of these strategies showed significant improvement in the VHT when compared to the fixed-time control. For the section between O’neal and Millerville, the mixed control strategy significantly improved the VHT values when compared to the fixed-time and ALINEA control strategies. However, for the section between Millerville and Sherwood, only ALINEA ramp metering strategy showed a significant improvement in the VHT when compared to the fixed-time control strategy.

Table 17
Section-by-section post hoc tukey test results for the different ramp metering strategies

| Dependent Variable | (I) Strategy | (J) Strategy | Mean Difference (I-J) | Std. Error | Sig. | 95% Confidence Interval | |
|----------------------|---------------|---------------|-----------------------|------------|------|-------------------------|-------------|
| | | | | | | Lower Bound | Upper Bound |
| Range-O’neal | Fixed Control | ALINEA | 92.36147* | 18.36670 | .000 | 48.1635 | 136.5594 |
| | | Mixed | 53.15462* | 18.36670 | .015 | 8.9567 | 97.3526 |
| | ALINEA | Fixed Control | -92.36147* | 18.36670 | .000 | -136.5594 | -48.1635 |
| | | Mixed | -39.20685 | 18.36670 | .092 | -83.4048 | 4.9911 |
| | Mixed | Fixed Control | -53.15462* | 18.36670 | .015 | -97.3526 | -8.9567 |
| | | ALINEA | 39.20685 | 18.36670 | .092 | -4.9911 | 83.4048 |
| O’neal-Millerville | Fixed Control | ALINEA | 38.98541 | 23.96649 | .243 | -18.6880 | 96.6588 |
| | | Mixed | 99.75765* | 23.96649 | .000 | 42.0843 | 157.4310 |
| | ALINEA | Fixed Control | -38.98541 | 23.96649 | .243 | -96.6588 | 18.6880 |
| | | Mixed | 60.77224* | 23.96649 | .037 | 3.0989 | 118.4456 |
| | Mixed | Fixed Control | -99.75765* | 23.96649 | .000 | -157.4310 | -42.0843 |
| | | ALINEA | -60.77224* | 23.96649 | .037 | -118.4456 | -3.0989 |
| Millerville-Sherwood | Fixed Control | ALINEA | 69.59992* | 25.19885 | .021 | 8.9610 | 130.2389 |
| | | Mixed | 39.65881 | 25.19885 | .265 | -20.9801 | 100.2978 |
| | ALINEA | Fixed Control | -69.59992* | 25.19885 | .021 | -130.2389 | -8.9610 |
| | | Mixed | -29.94111 | 25.19885 | .465 | -90.5801 | 30.6978 |
| | Mixed | Fixed Control | -39.65881 | 25.19885 | .265 | -100.2978 | 20.9801 |
| | | ALINEA | 29.94111 | 25.19885 | .465 | -30.6978 | 90.5801 |

Optimal Ramp Metering Strategy

The results showed that none of the adaptive ramp metering strategies affected the traffic conditions on the eastbound direction. The current traffic conditions on this direction are free flowing with the fixed-time strategy; hence, no further improvements could be achieved. For the westbound direction, both the ALINEA and the mixed strategy cases showed significant improvements in the traffic conditions compared to the fixed-time control. More specifically, three main locations benefited the most from both strategies. When the performance of the two strategies was compared, the mixed control was superior to ALINEA local control.

In summary, the analysis results showed the current demand on the eastbound direction can be controlled by the fixed-time control. Whereas, for the westbound direction, the mixed strategies (HERO coordinated strategy at the locations in Figure 3 and ALINEA local strategy at the other locations) is recommended to be implemented.

Cost Estimate of the Optimal Strategy

Based on the previous discussion, the mixed strategy was recommended to be implemented on the westbound direction on I-12. Whereas, for the eastbound, the fixed-control was recommended to remain in operation. Therefore, in order to implement this strategy, a rough cost estimate was prepared. This estimate includes the prices of the detectors and the control units. Implementing the optimal strategy requires detectors to be placed on the downstream of each on-ramp (to detect the downstream traffic conditions), detectors to be placed on the ramps (to detect the ramp queues, to measure the traffic arrivals and departures, and to detect the vehicle presence at the on-ramp entrance to I-12), and control units to control the signal timing based on the traffic conditions measured by the aforementioned detectors).

The required number of detectors for all the ramps' locations are 56. The unit price of each detector according to the Office of the Assistant Secretary for Research and Technology (OST-R) is around \$500. As a result, the total detectors' cost adds up to around \$28,000. For the control units, each ramp location requires one unit which adds up to 8 units for the 8 metered ramps. The unit price for each control unit according to the OST-R is \$20,000. This makes the total cost for the control units around \$160,000. As such, the total equipment price to implement the recommended strategy on the westbound direction is around \$188,000. This is a rough estimation that is subject to change according to the market prices.

CONCLUSIONS

This simulation-based evaluation study examined the effectiveness of different ramp metering strategies to improve the traffic conditions on I-12. The evaluation included a comparative speed analysis, travel time savings, and vehicles hours traveled (VHT) savings. The main objective was to identify the optimal ramp metering strategy that achieves more significant improvements in traffic conditions on the I-12 corridor. The tested strategies included the fixed-time ramp metering control, the ALINEA local ramp metering control, and the mixed strategy ramp metering control (which included a combination of HERO coordinated strategy and ALINEA local strategy). Queue override strategy was also used to flush the on-ramp queues in case they exceed certain limits. The base case in this study included the fixed-time ramp metering control with queue override strategy. The comparative analysis was performed between each of the ALINEA and mixed strategies and the base case. In the mixed strategy, the coordination was performed between two on-ramps on the eastbound and between two sets of two on-ramps on the westbound. For each strategy, the analysis was performed for the aggregated measures on the entire corridor as well as for each section of the corridor (a section is defined by a ramp meter location).

For the eastbound direction, the travel time for a vehicle traveling along the entire corridor was reduced by 6 seconds, when the mixed strategy was tested, and by 2 seconds, when the ALINEA strategy was tested. These travel time savings are not practically significant for a vehicle traveling along the 15 mile corridor. Similarly, the travel speed along the entire corridor was improved by 0.2 mph for the ALINEA strategy and 0.4 mph for the mixed strategy. These results affected the VHT values for both strategies. The VHT was reduced by 2.5 veh.hrs for the ALINEA strategy and by 6.5 veh.hrs for the mixed strategy. These results showed that none of the adaptive control strategies were able to improve the traffic conditions in the eastbound direction. This was investigated further using the statistical ANOVA analysis which showed no significant change in any of the used measures (speed, travel time, and VHT). These results were expected since the eastbound direction is operating with the fixed-time control at free flow conditions. This means that no further improvements can be expected or achieved for the operational characteristics of the corridor.

For the westbound direction, more significant results were obtained for all the measures. For ALINEA strategy, the average travel time along the corridor was reduced by around 20 seconds, the average speed was increased by around 1 mph, and the VHT were reduced by around 195 veh.hrs compared to the fixed-time control strategy. For the mixed strategy, the average travel time along the corridor was reduced by around 40 seconds, the average speed

was increased by around 2 mph, and the VHT were reduced by around 197 veh.hrs compared to the fixed-time control strategy. These improvements achieved by the ALINEA and the mixed strategy in the performance of the westbound direction are practically more significant than those achieved in the eastbound direction. The statistical comparative ANOVA analysis was performed to measure the statistical significance of these improvements. The analysis results showed that both the ALINEA and the mixed strategies significantly improved the overall operating conditions along the corridor when compared to the base case. The comparative ANOVA test between ALINEA and mixed strategies showed a significant improvement achieved by the coordination in mixed strategy in terms of the travel time only; whereas, the speed and the VHT values did not improve significantly.

Further analysis was performed for the westbound corridor to identify the ramp meters' locations that benefited the most from each strategy. The section-by-section calculated measures were used. The results showed that most of the sections (ramp meters' location did not show any improvements in any of the measures. Only three sections showed significant improvements in terms of the travel time and VHT (Range-O'neal, O'neal-Millerville, and Millerville-Sherwood), and two sections showed significant improvement in terms of the travel speed (Range-O'neal and O'neal-Millerville). For the section from Range to O'neal the travel time was reduced by around 45 seconds for ALINEA strategy; whereas, the reduction in the travel time was reduced to around 30 seconds for the mixed strategy. Similarly, the average speed for this section was increased by around 9 mph, for ALINEA strategy, and increased by around 5 mph, for the mixed strategy. As a result, the VHT on this section was reduced by around 100 veh.hrs, for ALINEA strategy, and reduced by around 60 veh.hrs, for the mixed strategy. For the section from O'neal to Millerville, the results showed more significant improvement for the mixed strategy when compared to the ALINEA local strategy. The reduction in the travel time was around 40 seconds for the mixed and 15 seconds for the ALINEA strategy. The speed results showed that while the ALINEA strategy was able to increase the speed at O'neal-Millerville section by around 3 mph, the mixed strategy increased the speed by around 13 mph for the same section. Similarly, the mixed strategy achieved more significant reductions in the VHT compared to the ALINEA. The VHT reduction for the latter strategy was around 40 veh.hrs; whereas, the former strategy achieved a VHT reduction by around 100 veh.hrs. For the section between Millerville and Sherwood, there was no improvement in the speed when using any of the adaptive control strategies. However, the travel time was reduced by around 20 seconds for ALINEA, and 15 seconds for the mixed strategy. More so, the VHT was reduced by around 75 veh.hrs for ALINEA, and 50 veh.hrs for the mixed strategy.

The speed profiles for the current traffic conditions in the westbound direction showed that the speed values over the aforementioned three sections were the lowest along the corridor. This means that there are bottlenecks at those specific sections. Using any of the adaptive strategies (ALINEA or mixed) was able to improve the traffic conditions at these sections. When the improvements achieved by the two strategies were compared to each other, the mixed strategy showed superiority to the ALINEA strategy on two sections, while the ALINEA was more superior on only one section.

The evaluation results show that none of the strategies achieved any significant improvements in the traffic conditions for the eastbound direction. However, for the westbound direction, the travel time, speed, and VHT improved significantly along the corridor. The section-by-section analysis for the westbound direction showed that while most of the sections did not experience any improvements, the traffic conditions on three sections were improved significantly. The results also showed that while the ALINEA strategy achieved more significant improvements at one section, the mixed strategy achieved more significant improvements at two sections. More so, the improvements achieved by the mixed strategy for the two sections were more significant than those achieved by ALINEA for the other section. Therefore, the mixed ramp metering strategy can be selected as the optimal strategy to operate the on-ramps of the I-12 corridor.

Overall, the results showed statistically significant improvements for the westbound direction. This was achieved for any of the adaptive control strategies (ALINEA and Mixed). While the improvements on some sections are significant statistically and practically, the overall improvements on the entire westbound direction were not practically significant. When investigating the collected video recordings for the westbound direction, they showed that one of the main reasons for the bottlenecks is the off-ramps spilling back on I-12. These spillbacks are resulting from the high off-ramps traffic volumes that are not accommodated by the traffic signals on the surface streets at the end of the off-ramps. This problem could be minimized if these traffic signals were coordinated with the ramp meters on I-12. This could help reduce the demand on the traffic signals on the surface streets and also allow longer green times for the off-ramp traffic at the surface streets' ends.

RECOMMENDATIONS

The following recommendations are made based on the findings of this study:

1. Further investigation should consider possible improvements from integrated corridor management. Coordination between the ramp meters and the traffic signals on the surface streets may help alleviating the spillbacks from the off-ramps on the interstate.
2. Further investigation should consider using mixed strategy according to the traffic condition and the time of operation. In other words, an on-ramp can be controlled by the fixed-time control for specific traffic conditions, but when these conditions change, according to the time of the day, an adaptive control can be activated.

ACRONYMS, ABBREVIATIONS, & SYMBOLS

| | |
|--------|--|
| LTRC | Louisiana Transportation Research Center |
| LADOTD | Louisiana Department of Transportation and Development |
| ATM | Active Traffic Management |
| DOTD | Department of Transportation and Development |
| DC | Demand Capacity |
| OCC | Occupancy |
| ALINEA | Asservissement Linéaire d'Entrée Auotroutière |
| ARMS | Advanced Real-time Metering System |
| ANN | Artificial Neural Network |
| BEEEX | Balanced Efficiency and Equity |
| WSDOT | Washington State Department of Transportation |
| FRESIM | FR _E eway SIMulation |
| SZM | Stratified Zone Ramp Metering |
| MCW | Monsh-Citylin-West Gate |
| IRIS | Intelligent Road Information System |
| VSL | Variable Speed Limit |
| HERO | Heuristic Ramp Metering |
| CPM | Crash Prediction Model |
| GPS | Global Positioning System |
| VAP | Vehicle Actuated Programming |

| | |
|--------|-----------------------------------|
| VHT | Vehicle hours travelled |
| ANOVA | Analysis Of Variance |
| MANOVA | Multivariate analysis of variance |

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APPENDIX A (VAP CODES FOR THE DIFFERENT RAMP METERING STRATEGIES)

This appendix shows detailed codes written in the Vehicle Actuated Programming (VAP) interface in VISSIM simulation software.

1. Fixed-Time Ramp Metering and ALINEA

```

PROGRAM DRUSILLAEB; /* FIXED timing vs Basic ALINEA Strategy */

VAP_FREQUENCY 1;

CONST
  Algorithm=2, /*Algorithm=1 if fixed timing , 2 if ALINEA, 3 if ALINEA with queue override tactic*/
  QueueOverRide=1, /*1 if queueoverride and 0 if no queueoverride*/

  QueueCountInterval = 20, /*update timing every 20 seconds*/
  OccupancyInterval = 20,
  GreenInterval = 2, /*Green time is 2 seconds to allow one vehicle at a time to enter the
mainline*/

  MaxRate = 1800, /*maximum ramp flow rate*/
  MinRate = 400, /*minimum ramp flow rate*/
  FixedRate = 900, /*fixed ramp flow rate, only rates at: 400, 450, 515, 600, 720, 900, 1200*/
  NumberMeterLane 1, /*Number of metered lanes*/

  PresenceDetector_1 = 49, /*Presence detectors on ramps based on which a vehicle calling to enter the mainline
is detected*/
  QueueDetector_Advance = 50, /*For queue detection at the end of the on-ramp*/
  Queue_Threshold = 0.1, /* For ramp queue detection */

  /*Data Collection Parameters*/
  StartTime=3600,
  EndTime=18000, /* 9000 for AM peak and 14400 for PM peak*/

  MAX_LANE = 4, /*number of lanes on the mainline*/
  KR = 70, /*ALINEA constant*/
  OCC_OPT = 0.29; /*Optimum or critical occupancy*/

/*****
/***** ARRAYS *****/
/*****

ARRAY
  detNo[ 4, 1 ] = [[24], [25], [26], [27]]; /*detectors array on the mainline /
/*****
/***** SUBROUTINES *****/
/*****

/*****Fixed Time Metering ***/
/*****
SUBROUTINE FIXED;

  IF Occupancy (PresenceDetector_1) > 0 THEN
    sg_red (1); /*If no vehicle waiting on the ramp switch the signal to red*/
  ELSE
    MeterPrevious :=FixedRate;

```



```

        MeterRate :=MeterPrevious;
        RedInt := (3600/MeterRate)*NumberMeterLane - GreenInterval;
    END;

    IF t_green (1) >=GreenInterval THEN
        sg_red (1);
    END;

    IF (t_red (1) >= RedInt) THEN      /* Red has reached the maximum so we need to check if there
are vehicles waiting to enter or not */
        IF Occupancy (PresenceDetector_1) > 0 THEN
            sg_green (1);
            START greenTimer1 ;
        END;
    END;

    IF greenTimer1 >= GreenInterval THEN
        sg_red (1);
    END;

    RESET (greenTimer1);
    STOP (greenTimer1).
/*****
/*****Fixed Time Metering Works with Queue Override*****/
/*****
SUBROUTINE FIXED2;
    IF Occupancy (PresenceDetector_1) > 0 THEN
        sg_red (1);      /*If no vehicle waiting on the ramp switch the signal to red*/
    ELSE
        MeterPrevious :=FixedRate;
        MeterRate :=MeterPrevious;
        RedInt := (3600/MeterRate)*NumberMeterLane - GreenInterval;
    END.
/*****
/*****ALINEA Strategy *****/
/*****
SUBROUTINE ALINEA;

    IF CountTimer = OccupancyInterval THEN
        TRACE (variable (MeterPrevious));
        IF OccupancyInterval = 1 THEN      /* set interval to 1 second for reporting */
            laneNo := 1;
            IF laneNo <= MAX_LANE THEN
                IF detNo[ laneNo, 1 ] > 0 THEN
                    S00Z001:      Occup:  Occup+ Occup_rate( detNo[ laneNo, 1 ]);
                    S00Z002:      laneNo : laneNo + 1;
                    S01Z002:
                    S02Z002:      GOTO S00Z002
                    S02Z003:      END;
                END;
                AverageOcc :  Occup/MAX_LANE;
                AvgOccup_DownStreamDet := AverageOcc;
            ELSE
                AvgOccup_DownStreamDet := Occup_DetDownStream / (OccupancyInterval);
            END;

            MeterRate := MeterPrevious + KR*(OCC_OPT-AvgOccup_DownStreamDet)*100;
            /*Metering Rate According to ALINEA equation.... If the occupancy downstream is larger
than the optimum, the meterrate will be less than the metering rate in the previous time step*/
            IF MeterRate >= MaxRate THEN

```

```

        MeterRate : MaxRate;
        RedInt : 3600/MeterRate)*NumberMeterLane - GreenInterval;
        MeterPrevious : MeterRate;
EISE
    IF MeterRate < MinRate THEN
        MeterRate : MinRate;
        RedInt : 3600/MeterRate)*NumberMeterLane - GreenInterval;
        MeterPrevious : MeterRate;
    ELSE
        RedInt : 3600/MeterRate)*NumberMeterLane - GreenInterval;
        MeterPrevious : MeterRate;
    END;
END;
/*****FlowRate on the mainline*****/
S00Z034: laneNo := 1;
S00Z035: IF laneNo <= MAX_LANE THEN
S01Z035:     IF detNo[ laneNo, 1 ] > 0 THEN
S02Z035:         SumVeh := SumVeh+ rear_ends( detNo[ laneNo, 1 ]);
S02Z036:         laneNo := laneNo + 1;
            GOTO S00Z035
        END;
    END;
    FlowRate := (SumVeh/OccupancyInterval)*3600;          /*the counted rear-ends are
converted into hourly flow rate*/

    TRACE (variable (AvgOccup_DownStreamDet, FlowRate));    /*record these data in
the output*/
    TRACE (variable (MeterRate, RedInt));

    RESET (CountTimer);
    Occup_DetDownStream :=0;
S00Z047: laneNo := 1;
S00Z048: IF laneNo <= MAX_LANE THEN
S01Z048:     IF detNo[ laneNo, 1 ] > 0 THEN
S02Z048:         clear_rear_ends( detNo[ laneNo, 1 ]);
S02Z049:         laneNo := laneNo + 1;
            GOTO S00Z048
        END;
    END;
    ELSE
S00Z055: laneNo := 1;
S00Z056: IF laneNo <= MAX_LANE THEN
S01Z056:     IF detNo[ laneNo, 1 ] > 0 THEN
S02Z056:         Occup:= Occup+ Occup_rate( detNo[ laneNo, 1 ]);
S02Z057:         laneNo := laneNo + 1;
            GOTO S00Z002
        END;
    END;
    AverageOcc := Occup/MAX_LANE;
    AvgOccup_DownStreamDet := AverageOcc;
END.
/*****Queue Override Tactic and Meter Operation *****/
SUBROUTINE MeterOperation;
/*Single-lane meter */
IF t_green (1) >=GreenInterval THEN
    IF (QueueOverRide AND QueueSpill) THEN
        sg_green (1); /*****
        MeterPrevious :=MaxRate; /*Do not start red and keep the ramp on green to flush*/

```

```

        IF (SimuTime >= StartTime) AND (SimuTime < EndTime) THEN
            MeterFlushTime : MeterFlushTime+1;
            TRACE variable SimuTime, MeterFlushTime ;
        END;
    ELSE
        sg_red (1);          /*If no queue on the ramp then switch the signal to red*/
    END;
END;

IF (t_red (1) >= RedInt) THEN          /* Red has reached the maximum so we need to check if there are vehicles
waiting to enter or not */
    IF Occupancy (PresenceDetector_1) > 0 THEN
        sg_green (1);
        START (greenTimer1);
    END;
END;

IF greenTimer1 >= GreenInterval THEN
    IF (QueueOverRide AND QueueSpill) THEN
        MeterPrevious :=MaxRate; /*Do not start red and keep the ramp on green to flush*/
        sg_green (1); /*******/
    ELSE
        sg_red (1);          /*If no queue on the ramp then switch the signal to red*/
    END;
END;

RESET (greenTimer1);
STOP (greenTimer1).
/*****
/*****This is the main Program*****/
/*****
TRACE (all);
START (QueueTimer);
START (CountTimer);
SimuTime : SimuTime + 1;

IF QueueTimer = (QueueCountInterval + 1) THEN
    AvgOccup_AdvanceQueueDet := Occup_AdvanceQueueDet / QueueCountInterval;
    QueueSpill := AvgOccup_AdvanceQueueDet >=Queue_Threshold;
    RESET (QueueTimer);
    Occup_AdvanceQueueDet := 0;
ELSE
    Occup_AdvanceQueueDet := Occup_AdvanceQueueDet + Occup_rate (QueueDetector_Advance);
END;

IF Algorithm = 1 THEN
    GOSUB FIXED;
ELSE
    IF Algorithm = 2 THEN
        GOSUB FIXED2;
        GOSUB MeterOperation;
    ELSE
        IF Algorithm = 3 THEN
            GOSUB ALINEA;
            GOSUB MeterOperation;
        END;
    END;
END;

END.
/*****

```

2. LINKED and ALINEA Ramp Metering

```

PROGRAM DRUSILLAEB; /* ALINEA - LINKED Strategy */

VAP_FREQUENCY 1;

CONST
  QueueOverride=1,          /*1 if queueoverride and 0 if no queueoverride*/
  Queue_Threshold = 0.1,   /* For ramp queue detection */
  Max_Threshold= 0.3, /*activation threshold for linked control.3*/
  Min_Threshold= 0.15, /*deactivation threshold.15*/
  StartTime= 3600,
  EndTime= 18000, /* 9000 for AM peak and 14400 for PM peak /
  QueueCountInterval = 20, /*update timing every 20 seconds*/
  OccupancyInterval = 20,
  GreenInterval = 2,          /*Green time is 2 seconds to allow one vehicle at a time to enter the
mainline*/
  MaxRate = 1800,            /*maximum ramp flow rate*/
  MinRate = 400,            /*minimum ramp flow rate*/
  NumberMeterLane_1 1, /*Number of metered lanes- Location 1*/
  NumberMeterLane_2 1, /*Number of metered lanes- Location 2*/
  MAX_LANE_1 = 4,          /*number of lanes on the mainline-1to3*/
  MAX_LANE_2 = 7,          /*number of lanes on the mainline-4to6*/
  PresenceDetector_1 = 118, /*Presence detectors on ramps based on which a vehicle calling to enter the mainline
is detected*/
  PresenceDetector_2 = 113,
  QueueDetector_Advance_1 = 119,
  QueueDetector_Advance_2 = 114,
  QueueDetector_Departure_1 = 165,
  QueueDetector_Departure_2 = 167,
  ArrivalDetector_1 = 166,
  ArrivalDetector_2 168,
  KR = 70,                  /*ALINEA constant*/
  OCC_OPT = 0.29,          /*Optimum or critical occupancy*/
  Desired_Density= 0.29, /*(veh/mile/lane) at merging area or downstream bottleneck, shall be
optimize.29*/
  W_max_o_1= 40 /*maximum admissible number of vehicles in the queue of on-ramp 1000ft(lenght of
ramp)/24ft(per eahc vehicle)*/
  W_max_o_2= 20 /*maximum admissible number of vehicles in the queue of the on-ramp 500ft (lenght
of ramp)/24ft (per eahc vehicle)*/

/***** ARRAYS *****/
/*****
ARRAY
  detNo[ 7, 1 ] = [ 34], [35], [36], [120], [115], [116], [117]]; /*detectors array on the mainline*/
/*****
/***** SUBROUTINES *****/
/*****
/***** Queue Override Meter Operation *****/
/*****
SUBROUTINE QOverride1;

  IF t_green (1) >=GreenInterval THEN
    IF (QueueOverride AND QueueSpill_1) THEN
      sg_green (1); /******
      MeterPrevious_1 :=MaxRate;          /*Do not start red and keep the ramp on green to
flush*/

      IF (SimuTime >= StartTime) AND (SimuTime < EndTime) THEN
        MeterFlushTime_1 : MeterFlushTime_1+1;
        TRACE variable SimuTime, MeterFlushTime_1 ;
      END;

```

```

ELSE
    sg_red (1);          /*If no queue on the ramp then switch the signal to red*/
END;
END;

IF (t_red (1) >= RedInt_1) THEN /* Red has reached the maximum so we need to check if there are vehicles
waiting to enter or not */
    IF Occupancy(PresenceDetector_1) > 0 THEN
        sg_green (1);
        START (greenTimer1);
    END;
END;

IF greenTimer1 >= GreenInterval THEN
    IF (QueueOverRide AND QueueSpill_1) THEN
        MeterPrevious_1 :=MaxRate;          /*Do not start red and keep the ramp on green to
flush*/
    ELSE
        sg_green (1);
    ELSE
        sg_red (1);          /*If no queue on the ramp then switch the signal to red*/
    END;
END;

RESET (greenTimer1);
STOP (greenTimer1).
/*****
/*****Meter Operation*****/
/*****
SUBROUTINE MeterOperation1;

IF t_green (1) >=GreenInterval THEN
    sg_red (1);          /*If no queue on the ramp then switch the signal to red*/
END;
IF (t_red (1) >= RedInt_1) THEN          /* Red has reached the maximum so we need to check if there are vehicles
waiting to enter or not */
    IF Occupancy (PresenceDetector_1) > 0 THEN
        sg_green (1);
        START (greenTimer1);
    END;
END;
IF greenTimer1 >= GreenInterval THEN
    sg_red (1);          /*If no queue on the ramp then switch the signal to red*/
END;

RESET (greenTimer1);
STOP (greenTimer1).
/*****
/*****RAMP TWO*****/
/*****
/*****Queue Override Meter Operation*****/
/*****
SUBROUTINE QOverride2;

IF t_green(2) >=GreenInterval THEN
    IF (QueueOverRide AND QueueSpill_2) THEN
        sg_green(2); /******/
        MeterPrevious_2 := MaxRate;          /*Do not start red and keep the ramp on green to
flush*/

```

```

IF (SimuTime >= StartTime) AND (SimuTime < EndTime) THEN
    MeterFlushTime_2 : MeterFlushTime_2+1;
    TRACE variable SimuTime, MeterFlushTime_2 ;
END;
ELSE
    sg_red(2);          /*If no queue on the ramp then switch the signal to red*/
END;
END;

IF (t_red(2) >= RedInt_2) THEN          /* Red has reached the maximum so we need to check if there are vehicles
waiting to enter or not */
    IF Occupancy (PresenceDetector_2) > 0 THEN
        sg_green(2);
        START(greenTimer2);
    END;
END;

IF greenTimer2 >= GreenInterval THEN
    IF (QueueOverRide AND QueueSpill_2) THEN
        MeterPrevious_2 :=MaxRate;          /*Do not start red and keep the ramp on green to
flush*/
        sg_green(2); /*******/
    ELSE
        sg_red(2);          /*If no queue on the ramp then switch the signal to red*/
    END;
END;

RESET (greenTimer2);
STOP (greenTimer2).
/*****/
/*****Meter Operation*****/
/*****/
SUBROUTINE MeterOperation2;

IF MeterRate_2 >0 THEN
    IF t_green (2) >=GreenInterval THEN
        sg_red (2);          /*If no queue on the ramp then switch the signal to red*/
    END;
    IF (t_red (2) >= RedInt_2) THEN          /* Red has reached the maximum so we need to check if there
are vehicles waiting to enter or not */
        IF Occupancy (PresenceDetector_2) > 0 THEN
            sg_green (2);
            START greenTimer2 ;
        END;
    END;
    IF greenTimer2 >= GreenInterval THEN
        sg_red (2);          /*If no queue on the ramp then switch the signal to red*/
    END;
ELSE
    sg_red(2);
END;

RESET (greenTimer2);
STOP (greenTimer2).
/*****/
/*****LINKED*****/
/*****/
SUBROUTINE LINKED;

IF CountTimer = OccupancyInterval THEN
S00e001:         laneNo_2 := 4;
S00e002:         IF laneNo_2 <= MAX_LANE_2 THEN

```

```

S01e002:          IF detNo[ laneNo_2, 1 ] > 0 THEN
S02e002:          Occup_2:= Occup_2+ Occup_rate( detNo[ laneNo_2, 1 ]);
S02e003:          laneNo_2 := laneNo_2 + 1;
                  GOTO S00e002
                  END;
                END;

                Occupancy_2 : Occup_2;
                AverageOcc_2 := Occupancy_2/(MAX_LANE_2 - MAX_LANE_1);
                AvgOccup_DownStreamDet_2 := AverageOcc_2;
                Occup_2 := 0;

                OptimumFlowControlramp_2 := MeterPrevious_2 + KR*(OCC_OPT-
                AvgOccup_DownStreamDet_2)*100;
                /*Metering Rate According to ALINEA equation.If the occupancy downstream is larger than
                the optimum, the meterrate will be less than the metering rate in the previous time step*/

                OptimumQueueControlramp_2 := (((-1/QueueCountInterval)*(W_max_o_2-
                Queue_Length_2))+RampDemandPrevious_2)*3600 /*arriving ramp demand*/
                W_min_o2 :=
                (((Queue_Length_1+Queue_Length_2)*(W_max_o_2))/(W_max_o_1+W_max_o_2));
                LocalControlMeterRate_2 := (((-1/QueueCountInterval)*(W_min_o2-
                Queue_Length_2))+RampDemandPrevious_2)*3600;

                IF (OptimumFlowControlramp_2 < LocalControlMeterRate_2) THEN
                    min_rate_2 : OptimumFlowControlramp_2;
                ELSE
                    min_rate_2 : LocalControlMeterRate_2;
                END;
                IF min_rate_2 > OptimumQueueControlramp_2 THEN
                    CoordinationMeterRate_2 : min_rate_2;
                ELSE
                    CoordinationMeterRate_2 : OptimumQueueControlramp_2;
                END;
                MeterRate_2 := CoordinationMeterRate_2;
                RedInt_2 := (3600/MeterRate_2 *NumberMeterLane_2 - GreenInterval;
                MeterPrevious_2 := MeterRate_2;

                /******Queue on Ramp2******/
                Arrival_2 := rear_ends(ArrivalDetector_2) ;
                Departure_2 := rear_ends(QueueDetector_Departure_2) ;
                Queue_Length_2 := (Arrival_2-Departure_2) + Queue_Length_Previous_2;

                IF (Queue_Length_2 > 0) THEN
                    Queue_Length_2 : Queue_Length_2;
                ELSE
                    Queue_Length_2 : 0;
                END;
                Queue_Length_Previous_2 := Queue_Length_2;
                RampDemand_CurrentInterval_2 := (Arrival_2)/OccupancyInterval ;
                RampDemandPrevious_2 := RampDemand_CurrentInterval_2;

S001001:          laneNo_1 := 1;
S001002:          IF laneNo_1 <= MAX_LANE_1 THEN
S011002:          IF detNo[ laneNo_1, 1 ] > 0 THEN
S021002:          Occup_1:= Occup_1+ Occup_rate( detNo[ laneNo_1, 1 ]);
S021003:          laneNo_1 := laneNo_1 + 1;
                  GOTO S001002
                  END;
                END;
                Occupancy_1 : Occup_1;

```

```

AverageOcc_1 := Occupancy_1/MAX_LANE_1;
AvgOccup_DownStreamDet_1 := AverageOcc_1;
Occup_1 := 0;

OptimumFlowControlramp_1 := MeterPrevious_1 + KR*(OCC_OPT-
AvgOccup_DownStreamDet_1)*100;
OptimumQueueControlramp_1 := ((-1/QueueCountInterval)*(W_max_o_1 -
Queue_Length_1)+RampDemandPrevious_1); /*arriving ramp demand*/

IF (OptimumFlowControlramp_1 >= OptimumQueueControlramp_1) THEN
    MeterRate_1 : OptimumFlowControlramp_1;
ELSE
    MeterRate_1 : OptimumQueueControlramp_1;
END;

IF MeterRate_1 >= MaxRate THEN
    MeterRate_1 : MaxRate;
    RedInt_1 : 3600/MeterRate_1 NumberMeterLane_1 - GreenInterval;
    MeterPrevious_1 : MeterRate_1;
ELSE
    IF MeterRate_1 < MinRate THEN
        MeterRate_1 : MinRate;
        RedInt_1 : 3600/MeterRate_1 NumberMeterLane_1 - GreenInterval;
        MeterPrevious_1 : MeterRate_1;
    ELSE
        RedInt_1 : 3600/MeterRate_1 NumberMeterLane_1 - GreenInterval;
        MeterPrevious_1 : MeterRate_1;
    END;
END;

/*****Queue on Ramp1*****/
Arrival_1 := rear_ends(ArrivalDetector_1);
Departure_1 := rear_ends(QueueDetector_Departure_1);
Queue_Length_1 := (Arrival_1-Departure_1) + Queue_Length_Previous_1;

IF (Queue_Length_1 > 0) THEN
    Queue_Length_1 : Queue_Length_1;
ELSE
    Queue_Length_1 : 0;
END;
Queue_Length_Previous_1 := Queue_Length_1;
RampDemand_CurrentInterval_1 := (Arrival_1)/OccupancyInterval ;
RampDemandPrevious_1 := RampDemand_CurrentInterval_1;

RESET (CountTimer);
S001047: laneNo_2 := 4;
S001048: IF laneNo_2 <= MAX_LANE_2 THEN
S011048:     IF detNo[ laneNo_2, 1 ] > 0 THEN
S021048:         clear_rear_ends( detNo[ laneNo_2, 1 ] );
S021049:         laneNo_2 := laneNo_2 + 1;
GOTO S001048
    END;
END;

clear_rear_ends(ArrivalDetector_2);
clear_rear_ends(QueueDetector_Departure_2);

S001047: laneNo_1 := 1;
S001048: IF laneNo_1 <= MAX_LANE_1 THEN
S011048:     IF detNo[ laneNo_1, 1 ] > 0 THEN
S021048:         clear_rear_ends( detNo[ laneNo_1, 1 ] );
S021049:         laneNo_1 := laneNo_1 + 1;
GOTO S001048

```



```

                                END;
END;
clear_rear_ends(ArrivalDetector_1);
clear_rear_ends QueueDetector_Departure_1 ;

ELSE
S00o055: laneNo_2 := 4;
S00o056: IF laneNo_2 <= MAX_LANE_2 THEN
S01o056:     IF detNo[ laneNo_2, 1 ] > 0 THEN
S02o056:         Occup_2:= Occup_2+ Occup_rate( detNo[ laneNo_2, 1 ]);
S02o057:         laneNo_2 := laneNo_2 + 1;
                GOTO S00o056
                END;
END;

Occupancy_2 := Occup_2;
AverageOcc_2 := Occupancy_2/(MAX_LANE_2 - MAX_LANE_1);
AvgOccup_DownStreamDet_2 := AverageOcc_2;
Occup_2 := 0;

Arrival_2 := rear_ends(ArrivalDetector_2);
Departure_2 := rear_ends(QueueDetector_Departure_2);
Queue_Length_2 := (Arrival_2-Departure_2) + Queue_Length_Previous_2;

IF (Queue_Length_2 > 0) THEN
    Queue_Length_2 : Queue_Length_2;
ELSE
    Queue_Length_2 : 0;
END;

S001055: laneNo_1 := 1;
S001056: IF laneNo_1 <= MAX_LANE_1 THEN
S011056:     IF detNo[ laneNo_1, 1 ] > 0 THEN
S021056:         Occup_1:= Occup_1+ Occup_rate( detNo[ laneNo_1, 1 ]);
S021057:         laneNo_1 := laneNo_1 + 1;
                GOTO S001056
                END;
END;

Occupancy_1 := Occup_1;
AverageOcc_1 := Occupancy_1/MAX_LANE_1;
AvgOccup_DownStreamDet_1 := AverageOcc_1;
Occup_1 := 0;

Arrival_1 := rear_ends(ArrivalDetector_1);
Departure_1 := rear_ends(QueueDetector_Departure_1);
Queue_Length_1 := (Arrival_1-Departure_1) + Queue_Length_Previous_1;
IF (Queue_Length_1 > 0) THEN
    Queue_Length_1 : Queue_Length_1;
ELSE
    Queue_Length_1 : 0;
END;

END.
/*****
/*****ALINEA Strategy *****/
/*****
SUBROUTINE ALINEA;

IF CountTimer = OccupancyInterval THEN

S00k001: laneNo_1 := 1;

```

```

S00k002:          IF laneNo_1 <= MAX_LANE_1 THEN
S01k002:              IF detNo[ laneNo_1, 1 ] > 0 THEN
S02k002:                  Occup_1:= Occup_1+ Occup_rate( detNo[ laneNo_1, 1 ]);
S02k003:                  laneNo_1 := laneNo_1 + 1;
                      GOTO S00k002
                      END;
                END;

                Occupancy_1 : Occup_1;
AverageOcc_1 := Occupancy_1/MAX_LANE_1;
AvgOccup_DownStreamDet_1 := AverageOcc_1;

S00q001:          laneNo_2 := 4;
S00q002:          IF laneNo_2 <= MAX_LANE_2 THEN
S01q002:              IF detNo[ laneNo_2, 1 ] > 0 THEN
S02q002:                  Occup_2:= Occup_2+ Occup_rate( detNo[ laneNo_2, 1 ]);
S02q003:                  laneNo_2 := laneNo_2 + 1;
                      GOTO S00q002
                      END;
                END;

                Occupancy_2 := Occup_2;
AverageOcc_2 := Occupancy_2/(MAX_LANE_2 - MAX_LANE_1);
AvgOccup_DownStreamDet_2 := AverageOcc_2;

                Occup_1 := 0;
                Occup_2 := 0;

                OptimumFlowControlramp_1 := MeterPrevious_1 + KR*(OCC_OPT-
AvgOccup_DownStreamDet_1)*100;
                OptimumQueueControlramp_1 := ((-1/QueueCountInterval)*(W_max_o_1 -
Queue_Length_1)+RampDemandPrevious_1); /*arriving ramp demand*/

                IF (OptimumFlowControlramp_1 >= OptimumQueueControlramp_1) THEN
                    MeterRate_1 : OptimumFlowControlramp_1;
                ELSE
                    MeterRate_1 : OptimumQueueControlramp_1;
                END;

                IF MeterRate_1 >= MaxRate THEN
                    MeterRate_1 : MaxRate;
                    RedInt_1 : 3600/MeterRate_1 NumberMeterLane_1 - GreenInterval;
                    MeterPrevious_1 : MeterRate_1;
                ELSE
                    IF MeterRate_1 < MinRate THEN
                        MeterRate_1 : MinRate;
                        RedInt_1 : 3600/MeterRate_1 NumberMeterLane_1 - GreenInterval;
                        MeterPrevious_1 : MeterRate_1;
                    ELSE
                        RedInt_1 : 3600/MeterRate_1 NumberMeterLane_1 - GreenInterval;
                        MeterPrevious_1 : MeterRate_1;
                    END;
                END;

                END;

                OptimumFlowControlramp_2 := MeterPrevious_2 + KR*(OCC_OPT-
AvgOccup_DownStreamDet_2)*100;
                OptimumQueueControlramp_2 := ((-1/QueueCountInterval)*(W_max_o_2-
Queue_Length_2)+RampDemandPrevious_2); /*arriving ramp demand*/

                IF (OptimumFlowControlramp_2 >= OptimumQueueControlramp_2) THEN
                    MeterRate_2 : OptimumFlowControlramp_2;
                ELSE
                    MeterRate_2 : OptimumQueueControlramp_2;
                END;

```

```

IF MeterRate_2 >= MaxRate THEN
    MeterRate_2 : MaxRate;
    RedInt_2 : 3600/MeterRate_2 NumberMeterLane_2 - GreenInterval;
    MeterPrevious_2 : MeterRate_2;
ELSE
    IF MeterRate_2 < MinRate THEN
        MeterRate_2 : MinRate;
        RedInt_2 : 3600/MeterRate_2 NumberMeterLane_2 - GreenInterval;
        MeterPrevious_2 : MeterRate_2;
    ELSE
        RedInt_2 : 3600/MeterRate_2 NumberMeterLane_2 - GreenInterval;
        MeterPrevious_2 : MeterRate_2;
    END;
END;

END;

/*****Queue on Ramp*****/
Arrival_1 := rear_ends(ArrivalDetector_1);
Departure_1 := rear_ends(QueueDetector_Departure_1);
Queue_Length_1 := (Arrival_1-Departure_1) + Queue_Length_Previous_1;

IF (Queue_Length_1 > 0) THEN
    Queue_Length_1 : Queue_Length_1;
ELSE
    Queue_Length_1 : 0;
END;
Queue_Length_Previous_1 := Queue_Length_1;

RampDemand_CurrentInterval_1 := (Arrival_1)/OccupancyInterval ;
RampDemandPrevious_1 := RampDemand_CurrentInterval_1;

/*****Queue on Ramp*****/
Arrival_2 := rear_ends(ArrivalDetector_2);
Departure_2 := rear_ends(QueueDetector_Departure_2);
Queue_Length_2 := (Arrival_2-Departure_2) + Queue_Length_Previous_2;

IF (Queue_Length_2 > 0) THEN
    Queue_Length_2 : Queue_Length_2;
ELSE
    Queue_Length_2 : 0;
END;
Queue_Length_Previous_2 := Queue_Length_2;

RampDemand_CurrentInterval_2 := (Arrival_2)/OccupancyInterval ;
RampDemandPrevious_2 := RampDemand_CurrentInterval_2;

RESET (CountTimer);
laneNo_1 := 1;
S00b047: IF laneNo_1 <= MAX_LANE_1 THEN
S00b048:     IF detNo[ laneNo_1, 1 ] > 0 THEN
S01b048:         clear_rear_ends( detNo[ laneNo_1, 1 ] );
S02b048:         laneNo_1 := laneNo_1 + 1;
S02b049:         GOTO S00b048
            END;
END;

END;

clear_rear_ends(ArrivalDetector_1);
clear_rear_ends(QueueDetector_Departure_1);

```



```

SimuTime : SimuTime + 1;
TRACE(all);

IF QueueTimer = (QueueCountInterval + 1) THEN
    AvgOccup_AdvanceQueueDet_1 := Occup_AdvanceQueueDet_1 / QueueCountInterval;
    QueueSpill_1 := AvgOccup_AdvanceQueueDet_1 >= Queue_Threshold;

    AvgOccup_AdvanceQueueDet_2 := Occup_AdvanceQueueDet_2 / QueueCountInterval;
    QueueSpill_2 := AvgOccup_AdvanceQueueDet_2 >= Queue_Threshold;
    RESET (QueueTimer);
    Occup_AdvanceQueueDet_1 := 0;
    Occup_AdvanceQueueDet_2 := 0;
ELSE
    Occup_AdvanceQueueDet_1 := Occup_AdvanceQueueDet_1 + Occup_rate
(QueueDetector_Advance_1);
    Occup_AdvanceQueueDet_2 := Occup_AdvanceQueueDet_2 + Occup_rate
(QueueDetector_Advance_2);
END;

QMAX := Queue_Length_1/W_max_o_1;
IF ((QMAX>Max_Threshold) AND (AvgOccup_DownStreamDet_1>0.9*Desired_Density)) THEN
    GOSUB LINKED;
    GOSUB MeterOperation2;
    GOSUB MeterOperation1;
ELSE
    IF ((QMAX<Min_Threshold) OR (AvgOccup_DownStreamDet_1 < 0.8*Desired_Density))
THEN
        GOSUB ALINEA;
        GOSUB QOverride1;
        GOSUB QOverride2;
    ELSE
        GOSUB ALINEA;
        GOSUB QOverride1;
        GOSUB QOverride2;
    END;
END.

```

APPENDIX B (STATISTICAL ANALYSIS RESULTS)

This appendix shows detailed results of the MANOVA and Post HOC tests performed for calibrating the ALINEA parameters. The appendix also includes all the ANOVA tests performed on each section during comparative analysis of different strategies.

Table B-1
MANOVA results for ALINEA parameters calibration (East direction)

| Effect | | Value | F | Hypothesis df | Error df | Sig. |
|--------------------------|--------------------|------------|---------------------------|---------------|----------|-------|
| Intercept | Pillai's Trace | 1.000 | 47988607.652 ^c | 2.000 | 683.000 | .000 |
| | Wilks' Lambda | .000 | 47988607.652 ^c | 2.000 | 683.000 | .000 |
| | Hotelling's Trace | 140523.009 | 47988607.652 ^c | 2.000 | 683.000 | .000 |
| | Roy s Largest Root | 140523.009 | 47988607.652 ^c | 2.000 | 683.000 | .000 |
| DetDIst | Pillai's Trace | .008 | 1.302 | 4.000 | 1368.000 | .267 |
| | Wilks' Lambda | .992 | 1.302 ^c | 4.000 | 1366.000 | .267 |
| | Hotelling's Trace | .008 | 1.302 | 4.000 | 1364.000 | .267 |
| | Roy s Largest Root | .008 | 2.571 ^d | 2.000 | 684.000 | .077 |
| OptOCC | Pillai's Trace | .001 | .157 | 6.000 | 1368.000 | .988 |
| | Wilks' Lambda | .999 | .157 ^c | 6.000 | 1366.000 | .988 |
| | Hotelling's Trace | .001 | .157 | 6.000 | 1364.000 | .988 |
| | Roy s Largest Root | .001 | .281 ^d | 3.000 | 684.000 | .839 |
| KR | Pillai's Trace | .000 | .059 | 4.000 | 1368.000 | .994 |
| | Wilks' Lambda | 1.000 | .059 ^c | 4.000 | 1366.000 | .994 |
| | Hotelling's Trace | .000 | .059 | 4.000 | 1364.000 | .994 |
| | Roy s Largest Root | .000 | .107 ^d | 2.000 | 684.000 | .898 |
| DetDIst * OptOCC | Pillai's Trace | .001 | .059 | 12.000 | 1368.000 | 1.000 |
| | Wilks' Lambda | .999 | .059 ^c | 12.000 | 1366.000 | 1.000 |
| | Hotelling's Trace | .001 | .059 | 12.000 | 1364.000 | 1.000 |
| | Roy s Largest Root | .001 | .086 ^d | 6.000 | 684.000 | .998 |
| DetDIst * KR | Pillai's Trace | .001 | .047 | 8.000 | 1368.000 | 1.000 |
| | Wilks' Lambda | .999 | .047 ^c | 8.000 | 1366.000 | 1.000 |
| | Hotelling's Trace | .001 | .047 | 8.000 | 1364.000 | 1.000 |
| | Roy s Largest Root | .000 | .077 ^d | 4.000 | 684.000 | .989 |
| OptOCC * KR | Pillai's Trace | .000 | .025 | 12.000 | 1368.000 | 1.000 |
| | Wilks' Lambda | 1.000 | .025 ^c | 12.000 | 1366.000 | 1.000 |
| | Hotelling's Trace | .000 | .025 | 12.000 | 1364.000 | 1.000 |
| | Roy s Largest Root | .000 | .036 ^d | 6.000 | 684.000 | 1.000 |
| DetDIst * OptOCC * KR | Pillai's Trace | .001 | .037 | 24.000 | 1368.000 | 1.000 |
| | Wilks' Lambda | .999 | .036 ^c | 24.000 | 1366.000 | 1.000 |
| | Hotelling's Trace | .001 | .036 | 24.000 | 1364.000 | 1.000 |
| | Roy s Largest Root | .001 | .061 ^d | 12.000 | 684.000 | 1.000 |

Table B-2
MANOVA results for ALINEA parameters calibration (West direction)

| | Effect | Value | F | Hypothesis df | Error df | Sig. |
|-----------------------------|--------------------|-----------|--------------|---------------|----------|------|
| Intercept | Pillai's Trace | 1.000 | 5158584.207c | 2.000 | 683.000 | .000 |
| | Wilks' Lambda | .000 | 5158584.207c | 2.000 | 683.000 | .000 |
| | Hotelling's Trace | 15105.664 | 5158584.207c | 2.000 | 683.000 | .000 |
| | Roy s Largest Root | 15105.664 | 5158584.207c | 2.000 | 683.000 | .000 |
| DetDist | Pillai's Trace | .431 | 94.032 | 4.000 | 1368.000 | .000 |
| | Wilks' Lambda | .569 | 111.150c | 4.000 | 1366.000 | .000 |
| | Hotelling's Trace | .756 | 128.900 | 4.000 | 1364.000 | .000 |
| | Roy s Largest Root | .755 | 258.162d | 2.000 | 684.000 | .000 |
| OptOCC | Pillai's Trace | .007 | .757 | 6.000 | 1368.000 | .604 |
| | Wilks' Lambda | .993 | .756c | 6.000 | 1366.000 | .604 |
| | Hotelling's Trace | .007 | .756 | 6.000 | 1364.000 | .605 |
| | Roy s Largest Root | .006 | 1.315d | 3.000 | 684.000 | .268 |
| KR | Pillai's Trace | .002 | .301 | 4.000 | 1368.000 | .878 |
| | Wilks' Lambda | .998 | .300c | 4.000 | 1366.000 | .878 |
| | Hotelling's Trace | .002 | .300 | 4.000 | 1364.000 | .878 |
| | Roy s Largest Root | .002 | .581d | 2.000 | 684.000 | .559 |
| DetDist * OptOCC | Pillai's Trace | .028 | 1.636 | 12.000 | 1368.000 | .076 |
| | Wilks' Lambda | .972 | 1.637c | 12.000 | 1366.000 | .076 |
| | Hotelling's Trace | .029 | 1.638 | 12.000 | 1364.000 | .075 |
| | Roy s Largest Root | .022 | 2.488d | 6.000 | 684.000 | .022 |
| DetDist * KR | Pillai's Trace | .004 | .315 | 8.000 | 1368.000 | .961 |
| | Wilks' Lambda | .996 | .315c | 8.000 | 1366.000 | .961 |
| | Hotelling's Trace | .004 | .314 | 8.000 | 1364.000 | .961 |
| | Roy s Largest Root | .003 | .578d | 4.000 | 684.000 | .679 |
| OptOCC * KR | Pillai's Trace | .004 | .226 | 12.000 | 1368.000 | .997 |
| | Wilks' Lambda | .996 | .225c | 12.000 | 1366.000 | .997 |
| | Hotelling's Trace | .004 | .225 | 12.000 | 1364.000 | .997 |
| | Roy s Largest Root | .004 | .414d | 6.000 | 684.000 | .870 |
| DetDist * OptOCC * KR | Pillai's Trace | .019 | .542 | 24.000 | 1368.000 | .965 |
| | Wilks' Lambda | .981 | .541c | 24.000 | 1366.000 | .966 |
| | Hotelling's Trace | .019 | .541 | 24.000 | 1364.000 | .966 |
| | Roy s Largest Root | .013 | .730d | 12.000 | 684.000 | .723 |

Table B-3
ANOVA results for ALINEA parameters calibration (West direction)

| Source | Dependent Variable | Type III Sum of Squares | df | Mean Square | F | Sig. |
|--------------------------|--------------------|--------------------------|-----|----------------|-------------|------|
| Corrected Model | VHT | 6529084.312 ^b | 35 | 186545.266 | 11.886 | .000 |
| | Speed (MPH) | 207.563 ^c | 35 | 5.930 | 4.117 | .000 |
| Intercept | VHT | 6983951791.041 | 1 | 6983951791.041 | 444993.811 | .000 |
| | Speed (MPH) | 1727490.734 | 1 | 1727490.734 | 1199371.111 | .000 |
| DetDIst | VHT | 6204273.962 | 2 | 3102136.981 | 197.658 | .000 |
| | Speed (MPH) | 177.028 | 2 | 88.514 | 61.454 | .000 |
| OptOCC | VHT | 61663.784 | 3 | 20554.595 | 1.310 | .270 |
| | Speed (MPH) | 4.036 | 3 | 1.345 | .934 | .424 |
| KR | VHT | 13158.478 | 2 | 6579.239 | .419 | .658 |
| | Speed (MPH) | .361 | 2 | .180 | .125 | .882 |
| DetDIst * OptOCC | VHT | 75339.515 | 6 | 12556.586 | .800 | .570 |
| | Speed (MPH) | 11.591 | 6 | 1.932 | 1.341 | .236 |
| DetDIst * KR | VHT | 34551.395 | 4 | 8637.849 | .550 | .699 |
| | Speed (MPH) | 3.022 | 4 | .755 | .525 | .718 |
| OptOCC * KR | VHT | 5447.120 | 6 | 907.853 | .058 | .999 |
| | Speed (MPH) | 1.959 | 6 | .327 | .227 | .968 |
| DetDIst * OptOCC * KR | VHT | 134650.056 | 12 | 11220.838 | .715 | .738 |
| | Speed (MPH) | 9.566 | 12 | .797 | .553 | .879 |
| Error | VHT | 10735032.499 | 684 | 15694.492 | | |
| | Speed (MPH) | 985.186 | 684 | 1.440 | | |
| Total | VHT | 7001215907.852 | 720 | | | |
| | Speed (MPH) | 1728683.482 | 720 | | | |
| Corrected Total | VHT | 17264116.811 | 719 | | | |
| | Speed (MPH) | 1192.749 | 719 | | | |

Table B-4
Post Hoc (Tukey HSD) results for the detector distance parameter (West direction)

| Dependent Variable | (I) Detector Distance | (J) Detector Distance | Mean Difference (I-J) | Std. Error | Sig. | 95% Confidence Interval | |
|--------------------|-----------------------|-----------------------|-----------------------|------------|------|-------------------------|-------------|
| | | | | | | Lower Bound | Upper Bound |
| | | | | | | | |
| VHT | 200 | 500 | 143.4732 | 11.43623 | .000 | 116.6115 | 170.3349 |
| | | 1000 | -81.0322 | 11.43623 | .000 | -107.8939 | -54.1705 |
| | 500 | 200 | -143.4732 | 11.43623 | .000 | -170.3349 | -116.6115 |
| | | 1000 | -224.5054 | 11.43623 | .000 | -251.3670 | -197.6437 |
| | 1000 | 200 | 81.0322 | 11.43623 | .000 | 54.1705 | 107.8939 |
| | | 500 | 224.5054 | 11.43623 | .000 | 197.6437 | 251.3670 |
| Speed (MPH) | 200 | 500 | -.8111 | .10956 | .000 | -1.0684 | -.5538 |
| | | 1000 | .3774 | .10956 | .002 | .1201 | .6347 |
| | 500 | 200 | .8111 | .10956 | .000 | .5538 | 1.0684 |
| | | 1000 | 1.1885 | .10956 | .000 | .9312 | 1.4458 |
| | 1000 | 200 | -.3774 | .10956 | .002 | -.6347 | -.1201 |
| | | 500 | -1.1885 | .10956 | .000 | -1.4458 | -.9312 |

Table B-5
Post Hoc (Tukey HSD) results for the KR parameter (West direction)

| Dependent Variable | (I) Kr | (J) Kr | Mean Difference (I-J) | Std. Error | Sig. | 95% Confidence Interval | |
|--------------------|--------|--------|-----------------------|------------|-------|-------------------------|-------------|
| | | | | | | Lower Bound | Upper Bound |
| VHT | 60 | 70 | 6.7361 | 11.43623 | 0.826 | -20.1255 | 33.5978 |
| | | 80 | -3.5752 | 11.43623 | 0.948 | -30.4369 | 23.2865 |
| | 70 | 60 | -6.7361 | 11.43623 | 0.826 | -33.5978 | 20.1255 |
| | | 80 | -10.3113 | 11.43623 | 0.639 | -37.173 | 16.5504 |
| | 80 | 60 | 3.5752 | 11.43623 | 0.948 | -23.2865 | 30.4369 |
| | | 70 | 10.3113 | 11.43623 | 0.639 | -16.5504 | 37.173 |
| Speed (MPH) | 60 | 70 | -0.0447 | 0.10956 | 0.912 | -0.3021 | 0.2126 |
| | | 80 | 0.0051 | 0.10956 | 0.999 | -0.2523 | 0.2624 |
| | 70 | 60 | 0.0447 | 0.10956 | 0.912 | -0.2126 | 0.3021 |
| | | 80 | 0.0498 | 0.10956 | 0.892 | -0.2075 | 0.3071 |
| | 80 | 60 | -0.0051 | 0.10956 | 0.999 | -0.2624 | 0.2523 |
| | | 70 | -0.0498 | 0.10956 | 0.892 | -0.3071 | 0.2075 |

Table B-6
Post Hoc results (Tukey HSD) for the Optimum Occupancy
parameter (West direction)

| Dependent Variable | (I) Optimum Occupancy | (J) Optimum Occupancy | Mean Difference (I-J) | Std. Error | Sig. | 95% Confidence Interval | |
|--------------------|-----------------------|-----------------------|-----------------------|------------|------|-------------------------|-------------|
| | | | | | | Lower Bound | Upper Bound |
| VHT | .10 | .20 | 25.5293 | 13.2 | .215 | -8.4794 | 59.5380 |
| | | .30 | 11.2379 | 13.2 | .830 | -22.7708 | 45.2466 |
| | | .40 | 16.7501 | 13.2 | .583 | -17.2586 | 50.7588 |
| | .20 | .10 | -25.5293 | 13.2 | .215 | -59.5380 | 8.4794 |
| | | .30 | -14.2914 | 13.2 | .701 | -48.3001 | 19.7173 |
| | | .40 | -8.7792 | 13.2 | .910 | -42.7879 | 25.2295 |
| | .30 | .10 | -11.2379 | 13.2 | .830 | -45.2466 | 22.7708 |
| | | .20 | 14.2914 | 13.2 | .701 | -19.7173 | 48.3001 |
| | | .40 | 5.5122 | 13.2 | .975 | -28.4965 | 39.5209 |
| | .40 | .10 | -16.7501 | 13.2 | .583 | -50.7588 | 17.2586 |
| | | .20 | 8.7792 | 13.2 | .910 | -25.2295 | 42.7879 |
| | | .30 | -5.5122 | 13.2 | .975 | -39.5209 | 28.4965 |
| Speed (MPH) | .10 | .20 | -.1935 | .127 | .420 | -.5193 | .1323 |
| | | .30 | -.1120 | .127 | .812 | -.4378 | .2138 |
| | | .40 | -.1706 | .127 | .533 | -.4963 | .1552 |
| | .20 | .10 | .1935 | .127 | .420 | -.1323 | .5193 |
| | | .30 | .0815 | .127 | .918 | -.2443 | .4073 |
| | | .40 | .0230 | .127 | .998 | -.3028 | .3488 |
| | .30 | .10 | .1120 | .127 | .812 | -.2138 | .4378 |
| | | .20 | -.0815 | .127 | .918 | -.4073 | .2443 |
| | | .40 | -.0585 | .127 | .967 | -.3843 | .2673 |
| | .40 | .10 | .1706 | .127 | .533 | -.1552 | .4963 |
| | | .20 | -.0230 | .127 | .998 | -.3488 | .3028 |
| | | .30 | .0585 | .127 | .967 | -.2673 | .3843 |

Table B-7
ANOVA results for the Comparative analysis
section= Start-Essen (East direction)

| | | Sum of Squares | df | Mean Square | F | Sig. |
|-------------------------------|--------------------|----------------|----|-------------|------|------|
| Speed (MPH) | Between Strategies | .108 | 2 | .054 | .057 | .945 |
| | Within Strategies | 54.113 | 57 | .949 | | |
| | Total | 54.221 | 59 | | | |
| Average Travel Time (seconds) | Between Strategies | .028 | 2 | .014 | .057 | .945 |
| | Within Strategies | 13.911 | 57 | .244 | | |
| | Total | 13.939 | 59 | | | |
| VHT | Between Strategies | .422 | 2 | .211 | .058 | .944 |
| | Within Strategies | 206.801 | 57 | 3.628 | | |
| | Total | 207.223 | 59 | | | |

Table B-8
ANOVA results for the Comparative analysis
Section= Essen-Jefferson (East direction)

| | | Sum of Squares | df | Mean Square | F | Sig. |
|-------------------------------|--------------------|----------------|----|-------------|------|------|
| Speed (MPH) | Between Strategies | .096 | 2 | .048 | .463 | .632 |
| | Within Strategies | 5.920 | 57 | .104 | | |
| | Total | 6.016 | 59 | | | |
| Average Travel Time (seconds) | Between Strategies | .048 | 2 | .024 | .479 | .622 |
| | Within Strategies | 2.857 | 57 | .050 | | |
| | Total | 2.905 | 59 | | | |
| VHT | Between Strategies | .608 | 2 | .304 | .382 | .685 |
| | Within Strategies | 45.453 | 57 | .797 | | |
| | Total | 46.061 | 59 | | | |

Table B-9
ANOVA results for the Comparative analysis
Section= Jefferson-Airline (East direction)

| | | Sum of Squares | df | Mean Square | F | Sig. |
|-------------------------------|--------------------|----------------|----|-------------|-------|------|
| Speed (MPH) | Between Strategies | 29.826 | 2 | 14.913 | 1.101 | .339 |
| | Within Strategies | 771.889 | 57 | 13.542 | | |
| | Total | 801.715 | 59 | | | |
| Average Travel Time (seconds) | Between Strategies | 27.828 | 2 | 13.914 | 1.009 | .371 |
| | Within Strategies | 786.258 | 57 | 13.794 | | |
| | Total | 814.086 | 59 | | | |
| VHT | Between Strategies | 545.595 | 2 | 272.797 | 1.009 | .371 |
| | Within Strategies | 15403.16 | 57 | 270.231 | | |
| | Total | 15948.75 | 59 | | | |

Table B-10
ANOVA results for the Comparative analysis
Section= Airline-Sherwood (East direction)

| | | Sum of Squares | df | Mean Square | F | Sig. |
|-------------------------------|--------------------|----------------|----|-------------|-------|------|
| Speed (MPH) | Between Strategies | 14.199 | 2 | 7.100 | 0.799 | .459 |
| | Within Strategies | 513.257 | 57 | 9.005 | | |
| | Total | 527.456 | 59 | | | |
| Average Travel Time (seconds) | Between Strategies | 54.687 | 2 | 27.344 | .794 | .457 |
| | Within Strategies | 1963.032 | 57 | 34.439 | | |
| | Total | 2017.719 | 59 | | | |
| VHT | Between Strategies | 1062.445 | 2 | 531.223 | .813 | .449 |
| | Within Strategies | 37233.937 | 57 | 653.227 | | |
| | Total | 38296.382 | 59 | | | |

Table B-11
ANOVA results for the Comparative analysis
Section= Sherwood-Millerville (East direction)

| | | Sum of Squares | df | Mean Square | F | Sig. |
|-------------------------------|--------------------|----------------|----|-------------|------|------|
| Speed (MPH) | Between Strategies | .139 | 2 | .069 | .430 | .652 |
| | Within Strategies | 9.204 | 57 | .161 | | |
| | Total | 9.343 | 59 | | | |
| Average Travel Time (seconds) | Between Strategies | .523 | 2 | .262 | .441 | .646 |
| | Within Strategies | 33.849 | 57 | .594 | | |
| | Total | 34.372 | 59 | | | |
| VHT | Between Strategies | 3.623 | 2 | 1.812 | .099 | .906 |
| | Within Strategies | 1048.320 | 57 | 18.392 | | |
| | Total | .139 | 2 | .069 | .430 | .652 |

Table B-12
ANOVA results for the Comparative analysis
Section= Millerville-O'Neal (East direction)

| | | Sum of Squares | df | Mean Square | F | Sig. |
|-------------------------------|--------------------|----------------|----|-------------|------|------|
| Speed (MPH) | Between Strategies | .118 | 2 | .059 | .045 | .956 |
| | Within Strategies | 74.014 | 57 | 1.298 | | |
| | Total | 74.132 | 59 | | | |
| Average Travel Time (seconds) | Between Strategies | .256 | 2 | .128 | .062 | .940 |
| | Within Strategies | 116.922 | 57 | 2.051 | | |
| | Total | 117.178 | 59 | | | |
| VHT | Between Strategies | .798 | 2 | .399 | .010 | .990 |
| | Within Strategies | 2231.698 | 57 | 39.153 | | |
| | Total | 2232.496 | 59 | | | |

Table B-13
ANOVA results for the Comparative analysis
Section= O'Neal-Range (East direction)

| | | Sum of Squares | df | Mean Square | F | Sig. |
|-------------------------------|--------------------|----------------|----|-------------|------|------|
| Speed (MPH) | Between Strategies | .044 | 2 | .022 | .281 | .756 |
| | Within Strategies | 4.481 | 57 | .079 | | |
| | Total | 4.525 | 59 | | | |
| Average Travel Time (seconds) | Between Strategies | .365 | 2 | .182 | .284 | .754 |
| | Within Strategies | 36.597 | 57 | .642 | | |
| | Total | 36.961 | 59 | | | |
| VHT | Between Strategies | 4.625 | 2 | 2.313 | .168 | .846 |
| | Within Strategies | 784.972 | 57 | 13.771 | | |
| | Total | 789.597 | 59 | | | |

Table B-14
ANOVA results for the Comparative analysis
Section= Range-Juban (East direction)

| | | Sum of Squares | df | Mean Square | F | Sig. |
|-------------------------------|--------------------|----------------|----|-------------|-------|------|
| Speed (MPH) | Between Strategies | .128 | 2 | .064 | 2.077 | .135 |
| | Within Strategies | 1.757 | 57 | .031 | | |
| | Total | 1.885 | 59 | | | |
| Average Travel Time (seconds) | Between Strategies | .597 | 2 | .299 | 2.073 | .135 |
| | Within Strategies | 8.211 | 57 | .144 | | |
| | Total | 8.808 | 59 | | | |
| VHT | Between Strategies | 4.752 | 2 | 2.376 | .233 | .793 |
| | Within Strategies | 581.335 | 57 | 10.199 | | |
| | Total | 586.087 | 59 | | | |

Table B-15
ANOVA results for the Comparative analysis
Section= Juban-Walker (East direction)

| | | Sum of Squares | df | Mean Square | F | Sig. |
|-------------------------------|--------------------|----------------|----|-------------|------|------|
| Speed (MPH) | Between Strategies | .001 | 2 | .001 | .780 | .463 |
| | Within Strategies | .054 | 57 | .001 | | |
| | Total | .056 | 59 | | | |
| Average Travel Time (seconds) | Between Strategies | .012 | 2 | .006 | .780 | .463 |
| | Within Strategies | .444 | 57 | .008 | | |
| | Total | .456 | 59 | | | |
| VHT | Between Strategies | .552 | 2 | .276 | .012 | .988 |
| | Within Strategies | 1350.026 | 57 | 23.685 | | |
| | Total | 1350.578 | 59 | | | |

Table B-16
ANOVA results for the Comparative analysis
Section =Walker-End (East direction)

| | | Sum of Squares | df | Mean Square | F | Sig. |
|-------------------------------|--------------------|----------------|----|-------------|------|------|
| Speed (MPH) | Between Strategies | .000 | 2 | .000 | .474 | .625 |
| | Within Strategies | .007 | 55 | .000 | | |
| | Total | .007 | 57 | | | |
| Average Travel Time (seconds) | Between Strategies | .000 | 2 | .000 | .473 | .625 |
| | Within Strategies | .008 | 55 | .000 | | |
| | Total | .008 | 57 | | | |
| VHT | Between Strategies | 1.331 | 2 | .665 | .190 | .827 |
| | Within Strategies | 192.267 | 55 | 3.496 | | |
| | Total | 193.597 | 57 | | | |

Table B-17
ANOVA results for the Comparative analysis
Section = Start-Walker (West direction)

| | | Sum of Squares | df | Mean Square | F | Sig. |
|-------------------------------|--------------------|----------------|----|-------------|------|------|
| Speed (MPH) | Between Strategies | .000 | 2 | .000 | .006 | .994 |
| | Within Strategies | .110 | 57 | .002 | | |
| | Total | .110 | 59 | | | |
| Average Travel Time (seconds) | Between Strategies | .000 | 2 | .000 | .006 | .994 |
| | Within Strategies | .132 | 57 | .002 | | |
| | Total | .132 | 59 | | | |
| VHT | Between Strategies | .001 | 2 | .001 | .002 | .998 |
| | Within Strategies | 12.056 | 57 | .212 | | |
| | Total | 12.057 | 59 | | | |

Table B-18
ANOVA results for the Comparative analysis
Section = Walker-Juban (West direction)

| | | Sum of Squares | df | Mean Square | F | Sig. |
|-------------------------------|--------------------|----------------|----|-------------|------|------|
| Speed (MPH) | Between Strategies | .001 | 2 | .000 | .853 | .431 |
| | Within Strategies | .027 | 57 | .000 | | |
| | Total | .028 | 59 | | | |
| Average Travel Time (seconds) | Between Strategies | .007 | 2 | .003 | .854 | .431 |
| | Within Strategies | .218 | 57 | .004 | | |
| | Total | .224 | 59 | | | |
| VHT | Between Strategies | .142 | 2 | .071 | .025 | .976 |
| | Within Strategies | 163.696 | 57 | 2.872 | | |
| | Total | 163.838 | 59 | | | |

Table B-19
ANOVA results for the Comparative analysis
Section= Juban-Range (West direction)

| | | Sum of Squares | df | Mean Square | F | Sig. |
|-------------------------------|--------------------|----------------|----|-------------|-------|------|
| Speed (MPH) | Between Strategies | 1.051 | 2 | .526 | 9.321 | .000 |
| | Within Strategies | 3.214 | 57 | .056 | | |
| | Total | 4.265 | 59 | | | |
| Average Travel Time (seconds) | Between Strategies | 5.610 | 2 | 2.805 | 9.337 | .000 |
| | Within Strategies | 17.126 | 57 | .300 | | |
| | Total | 22.736 | 59 | | | |
| VHT | Between Strategies | 15.475 | 2 | 7.737 | 2.104 | .131 |
| | Within Strategies | 209.579 | 57 | 3.677 | | |
| | Total | 225.054 | 59 | | | |

Table B-20
ANOVA results for the Comparative analysis
Section = Range-O'Neal (West direction)

| | | Sum of Squares | df | Mean Square | F | Sig. |
|-------------------------------|--------------------|----------------|----|-------------|--------|------|
| Speed (MPH) | Between Strategies | 377.697 | 2 | 188.849 | 13.550 | .000 |
| | Within Strategies | 794.407 | 57 | 13.937 | | |
| | Total | 1172.104 | 59 | | | |
| Average Travel Time (seconds) | Between Strategies | 18433.025 | 2 | 9216.512 | 12.387 | .000 |
| | Within Strategies | 42410.151 | 57 | 744.038 | | |
| | Total | 60843.176 | 59 | | | |
| VHT | Between Strategies | 85954.876 | 2 | 42977.438 | 12.740 | .000 |
| | Within Strategies | 192281.331 | 57 | 3373.357 | | |
| | Total | 278236.207 | 59 | | | |

Table B-21
ANOVA results for the Comparative analysis
Section = O'Neal-Millerville (West direction)

| | | Sum of Squares | df | Mean Square | F | Sig. |
|-------------------------------|--------------------|----------------|----|-------------|-------|------|
| Speed (MPH) | Between Strategies | 1886.360 | 2 | 943.180 | 9.206 | .000 |
| | Within Strategies | 5839.842 | 57 | 102.453 | | |
| | Total | 7726.201 | 59 | | | |
| Average Travel Time (seconds) | Between Strategies | 11791.703 | 2 | 5895.852 | 8.478 | .001 |
| | Within Strategies | 39637.188 | 57 | 695.389 | | |
| | Total | 51428.891 | 59 | | | |
| VHT | Between Strategies | 101098.100 | 2 | 50549.050 | 8.800 | .000 |
| | Within Strategies | 327403.684 | 57 | 5743.924 | | |
| | Total | 428501.783 | 59 | | | |

Table B-22
ANOVA results for the Comparative analysis
Section = = Millerville-Sherwood (West direction)

| | | Sum of Squares | df | Mean Square | F | Sig. |
|-------------------------------|--------------------|----------------|----|-------------|-------|------|
| Speed (MPH) | Between Strategies | 45.756 | 2 | 22.878 | 1.943 | .153 |
| | Within Strategies | 671.121 | 57 | 11.774 | | |
| | Total | 716.877 | 59 | | | |
| Average Travel Time (seconds) | Between Strategies | 2751.358 | 2 | 1375.679 | 2.501 | .091 |
| | Within Strategies | 31349.168 | 57 | 549.985 | | |
| | Total | 34100.526 | 59 | | | |
| VHT | Between Strategies | 48756.26 | 2 | 24378.134 | 3.839 | .027 |
| | Within Strategies | 361939.62 | 57 | 6349.818 | | |
| | Total | 410695.88 | 59 | | | |

Table B-23
ANOVA results for the Comparative analysis
Section= Airline-Jefferson (West direction)

| | | Sum of Squares | df | Mean Square | F | Sig. |
|-------------------------------|--------------------|----------------|----|-------------|------|------|
| Speed (MPH) | Between Strategies | 4.522 | 2 | 2.261 | .257 | .775 |
| | Within Strategies | 502.112 | 57 | 8.809 | | |
| | Total | 506.634 | 59 | | | |
| Average Travel Time (seconds) | Between Strategies | 16.477 | 2 | 8.239 | .255 | .776 |
| | Within Strategies | 1842.399 | 57 | 32.323 | | |
| | Total | 1858.876 | 59 | | | |
| VHT | Between Strategies | 276.362 | 2 | 138.181 | .299 | .743 |
| | Within Strategies | 26326.305 | 57 | 461.865 | | |
| | Total | 26602.668 | 59 | | | |

Table B-24
ANOVA results for the Comparative analysis
Section = Jefferson-Essen (West direction)

| | | Sum of Squares | df | Mean Square | F | Sig. |
|-------------------------------|--------------------|----------------|----|-------------|--------|------|
| Speed (MPH) | Between Strategies | .025 | 2 | .013 | .414 | .663 |
| | Within Strategies | 1.731 | 57 | .030 | | |
| | Total | 1.756 | 59 | | | |
| Average Travel Time (seconds) | Between Strategies | .016 | 2 | .008 | .412 | .665 |
| | Within Strategies | 1.087 | 57 | .019 | | |
| | Total | 1.102 | 59 | | | |
| VHT | Between Strategies | 43.983 | 2 | 21.991 | 13.548 | .000 |
| | Within Strategies | 92.526 | 57 | 1.623 | | |
| | Total | 136.509 | 59 | | | |

Table B-25
ANOVA results for the Comparative analysis
Section = Essen-End (West direction)

| | | Sum of Squares | df | Mean Square | F | Sig. |
|-------------------------------|--------------------|----------------|----|-------------|------|------|
| Speed (MPH) | Between Strategies | 1.607 | 2 | .803 | .821 | .445 |
| | Within Strategies | 53.836 | 55 | .979 | | |
| | Total | 55.442 | 57 | | | |
| Average Travel Time (seconds) | Between Strategies | .323 | 2 | .161 | .839 | .437 |
| | Within Strategies | 10.573 | 55 | .192 | | |
| | Total | 10.895 | 57 | | | |
| VHT | Between Strategies | 3.051 | 2 | 1.526 | .376 | .689 |
| | Within Strategies | 1.607 | 2 | .803 | .821 | .445 |
| | Total | 53.836 | 55 | .979 | | |